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An Investigation into the Relationship between Bone Diagenesis and Funerary Treatment.

Volume I

By

Thomas J. Booth

Registration No. 100202186

Submitted for the Degree of Doctor of Philosophy

Department of Archaeology

University of Sheffield

March 2014

Abstract

After death, the skeleton of a vertebrate organism undergoes a variety of physical and chemical changes that lead to its destruction or fossilisation (diagenesis). The most common type of archaeological bone diagenesis consists of internal microscopic tunnelling produced by invasive microorganisms (bioerosion). There is evidence that an organism's intrinsic gut bacteria associated with bodily putrefaction are responsible for the most common type of bone bioerosion. Bacterial bioerosion of archaeological bone should be related to how early post mortem *treatment of a corpse affected bone exposure to putrefaction. Measures of bacterial bioerosion may aid taphonomic reconstructions of past funerary treatments of human remains. A plethora of variables can affect bodily decomposition, and it is uncertain how far bacterial bioerosion reflects anthropogenic or natural processes. Bone undergoes a variety of interrelated diagenetic changes over its depositional history and bacterial bioerosion must be understood within its diagenetic context.*

The purpose of this study was to determine how far microscopic examination of archaeological bone diagenesis may aid in reconstructions of funerary rites. This objective was addressed through the histological analysis of bone thin sections from 301 individual skeletons retrieved from 25 European Later Prehistoric and British Historical archaeological sites. Bacterial bioerosion within this assemblage was primarily influenced by neonatal status or waterlogged burial sediments. When the neonatal and anoxic-deposited remains were excluded, bacterial bioerosion was controlled by archaeological phase in a way that had been predicted based on known early post mortem *treatment and forensic models of bodily decomposition. Further diagenetic variables were also influenced by early taphonomic events, although these relationships were not as strong or as regular as those observed between funerary treatment and bacterial bioerosion. These findings suggested that microscopic analyses of bone diagenesis has useful applications to reconstructions of early post mortem processes, particularly funerary rites.*

Acknowledgements

This project was funded by a doctoral studentship grant from the U.K. Arts and Humanities Research Council. I could not have completed my research without this funding and I am extremely grateful for the support of the AHRC. I am also grateful to my original supervisors, Professors Andrew Chamberlain and Mike Parker Pearson, who both played a large part in formulating this project. They both kept an ear to the ground for potential samples and their advice and guidance were invaluable to the preparation and execution of this research. I'm particularly grateful for their efforts, as clearly this project was so unbearable that they both felt it necessary to leave the university before it all became too much.

To lose one supervisor may be regarded as a misfortune, to lose both looks like carelessness. Therefore I'd also like to thank Dr. Pia Nystrom and Professor John Barrett for agreeing to take over as my new supervisors in spite of my inauspiciousness. Both were responsible for providing plenty of healthy advice, guidance and criticism. I am particularly grateful to Pia for wading through my distended drafts and for some particularly crucial guidance regarding statistical tests. Thanks also to Dr. Lizzy Craig, who was also always a willing test subject for ideas. I am also grateful to Dr. Jane Rempel and Professor Dawn Hadley who were both integral to my successful application for the aforementioned funding.

This project would not have been possible without the help of the curators that granted access to sample collections. These people were also immensely helpful in responding to enquiries and providing detailed contextual information for each site: Peter Rowe at Tees Archaeology; Dr. Alison Sheridan at the National Museum of Scotland; Dr. Eamonn Kelly and Isabella Mulhall at the National Museum of Ireland; Mark Knight, Natasha Dodwell and Chris Evans at Cambridge Archaeological Unit; Geoff Morley of MOLES Archaeology; Dave Allen at the Hampshire Museum Service; Dr. Olivia Lelong at Glasgow University; Emily Hellewell and Professor Don Brothwell at the University of York; Dr. Karl-Goran Sjögren at the University of Gothenburg. Special thanks to Dr. Richard Madgwick at the University of Cardiff for helping with accessing and collecting the Danebury samples and for the reassurance that I was not the only person in the world who was interested in this topic.

Misery loves company and so I'd also like to thank my fellow human osteology PhD pilgrims (and splendid friends) for their help and support, as well as for allowing my involvement in

their extra-curricular activities: Linzi Harvey, Dr. Lauren McIntyre, Isabelle Heyerdahl-King, Jenny Crangle, Alison Atkin, Kyle Billington and Conrad Brimacombe. For similar reasons, thanks also to the supremely talented non-human osteology wizards and warlocks: Lizzie Wright, Angela Trentacoste, Dr. Hannah Russ, Dr. Sarah Viner and Lenny Salvagno. Additional thanks to Dr. Chrissy Collins, Dr. Diana Swales, Dr. Katie Hemer, Dr. Vicky Crewe and Dr. Gareth Perry for their help, advice and technical assistance. Thanks also to all those past research students whose samples I incorporated into my own work, particularly Dr. Lorraine White, whose previous research laid the foundations for this current project and whose correspondence was crucial to its design. Finally, thanks to my lovely and remarkable future wife Jemma Brimblecombe, whose fathomless love and support were a constant source of reassurance and whose consistent disinterest and bewilderment with this entire endeavour ensured I remained well-grounded.

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1 INTRODUCTION

After the death of a vertebrate organism, the skeleton is subject to a variety of physico-chemical changes that lead to its destruction or fossilisation (Hedges 2002; Trueman & Martill 2002; Nielsen-Marsh *et al.* 2007; Smith *et al.* 2007; Lee-Thorp & Sealy 2008). These changes are referred to as diagenesis. Bone diagenesis consists of three processes: the breakdown and removal of bone proteins, the dissolution or alteration of the bone mineral matrix, and infiltration of the bone by exogenous substances. The effects of diagenesis can change the macroscopic properties and appearance of bone samples. However, the most effective way of measuring diagenesis is through the analysis of changes to the bone microstructure.

The most common diagenetic pathway observed within archaeological bone is microbial attack (Hackett 1981; Turner-Walker *et al.* 2002; Jans *et al.* 2004; Nielsen-Marsh *et al.* 2007). The microorganisms responsible for this type of diagenesis invade and travel through the bone microstructure in order to exploit the resident proteins. This type of biologically-mediated attack is called bioerosion. The progress of microbes through the microstructure produces characteristic tunnels called micro-foci of destruction (MFD) (Hackett 1981). Fungal and bacterial organisms produce different types of MFD named Wedl and non-Wedl respectively (Hackett 1981).

Bacterial non-Wedl MFD represent the most abundant forms of microbial tunnelling found within archaeological bones (Hackett 1981; Turner-Walker *et al.* 2002; Jans *et al.* 2004; Nielsen-Marsh *et al.* 2007). The extent of bacterial bioerosion within archaeological bone is often variable. Early theories regarding the origins and variation in bacterial bone bioerosion were concerned with soil microorganisms that invaded the bone post-skeletonisation (Marchiafava *et al.* 1974; Hackett 1981; Piepenbrink 1986; 1989; Hanson & Buikstra 1987; Yoshino *et al.* 1991; Grupe & Dreses-Werringloer 1993). An exogenous model of bacterial attack suggests that variation in bacterial bioerosion amongst archaeological bones was controlled by differences in the burial environment that affected the abundance and nature of resident soil microorganisms (Turner-Walker & Jans 2008).

However, successive studies have indicated that non-Wedl MFD are likely to have been formed by the intrinsic gut bacteria of the dead organism (Child 1995a; 1995b; Bell *et al.* 1996; Jans *et al.* 2004; Nielsen-Marsh *et al.* 2007). These types of bacteria escape into the bone during early post mortem soft tissue putrefaction (Polson *et al.* 1985; Child 1995a; 1995b). In this

endogenous model, bacterial bioerosion of bone would be controlled by the extent to which the skeleton was exposed to the deleterious effects of putrefaction. This factor would be predominantly influenced by early *post mortem* taphonomic processes (Bell *et al.* 1996; Hedges 2002; Jans *et al.* 2004; Nielsen-Marsh *et al.* 2007).

The status of bacterial bioerosion as a gauge of the extent to which an archaeological bone was exposed to putrefaction bacteria presents a potentially useful prospect for the study of funerary treatment. It is possible that certain kinds of funerary rites will leave characteristic signatures of bacterial bioerosion within archaeological bone microstructure (Parker Pearson *et al.* 2005). If this scenario could be proven, the study of bone diagenesis would provide a method of distinguishing between discrete funerary rites that leave similar archaeological records. For instance, analysis of bone diagenesis may provide a method of determining the processes which led to the formation of disarticulated archaeological human bone assemblages. Methods of diagenetic analysis may also help to identify hidden complexities in funerary treatment that could not have been discerned through the analysis of the archaeological evidence alone (Parker Pearson *et al.* 2005).

Relationships between early post mortem treatment and bacterial bioerosion have been recorded within certain archaeological assemblages (Jans *et al.* 2004; Nielsen-Marsh *et al.* 2007; Smith *et al.* 2007). However, there have been no investigations into whether specific funerary treatments of human remains produce characteristic signatures of bacterial bone bioerosion. Processes such as dismemberment separate the bone from the putrefying viscera within the early post mortem period and would be expected to have an immediate effect on any related bacterial bone bioerosion. However, rites such as coffin burial or wrapping only slow the rate of bodily decomposition, and may have a more nuanced influence on the bacterial attack of bone (Mant 1987; Galloway *et al.* 1989; Mann *et al.* 1990; Aturaliya & Lukasewycz 1999; Fereira & Cunha 2013). Therefore, it has yet to be established which, if any, types of funerary treatment have a detectable impact on bodily putrefaction and internal bone bioerosion.

Seasonality is most often cited as the factor that has the largest effect on the nature of bodily decomposition (Rodriguez & Bass 1983; 1985; Mann *et al.* 1990; Manhein 1997; Bass 1997; Wilson *et al.* 2007; Meyer *et al.* 2013). Anoxic burial environments such as waterlogged graves can arrest putrefaction to an extent that sometimes permits soft tissue to persevere over extended periods of time (Polson *et al.* 1985; Cotton *et al.* 1987; Mant 1987; Janaway 1996; Turner & Wiltshire 1999; Fielder & Graw 2003; Wilson *et al.* 2007). It has yet to be determined

whether the effects of anthropogenic processes on bacterial bone bioerosion can be distinguished from changes elicited by the burial environment. Moreover, the results of more recent experimental research into the origins of non-Wedl MFD have suggested that the role of exogenous soil bacteria cannot be discounted (Fernández-Jalvo *et al.* 2010; Turner-Walker 2008; 2012). The strength of the relationship between early post mortem processes and bacterial bone bioerosion is questionable.

There are a series of further diagenetic changes that a bone can undergo that may also relate to how the body was treated within the early post mortem period. For instance, the presence of fungal Wedl tunnelling within archaeological bone microstructure has been linked to processes that would have prevented endogenous bacteria from exploiting the bone proteins, such as butchery (Jans *et al.* 2004). The presence of particular materials within the bone matrix could be reflective of decompositional environments that affected the progression of putrefaction (Hollund *et al.* 2012). There is a requirement to understand bacterial bioerosion within its diagenetic context.

1.1 RESEARCH QUESTIONS

The primary focus of the current study was putrefactive bioerosion of bone. However, the requirement to understand this variable amongst overall diagenetic change meant that the objectives had to be framed in reference to whole bone diagenesis. The main aims of this study were to determine whether there was a relationship between bone diagenesis and funerary treatment and decide whether the nature of any associations suggested that measures of bone diagenesis could be useful in reconstructions of funerary treatment. These aims can be summed up in the following research questions:

1. Is there a relationship between funerary treatment and bone diagenesis that is strong enough to be detected by microscopic analysis of archaeological bone?

2. Does the relationship between bone diagenesis and funerary treatment conform to predictive models of diagenesis inferred by studies of cadaveric decomposition?

3. Is the strength and nature of the relationship between bone diagenesis and funerary rite such that certain treatments can be said to produce characteristic patterns of diagenesis that can be recognised through the microscopic analysis of archaeological bone microstructure?

4. How can measures of bone diagenesis, particularly the microscopic assessment of archaeological bones, be usefully employed in reconstructions of funerary processes?

These questions were addressed in the present study through the microscopic analysis of diagenetic changes to archaeological bones recovered from European Later Prehistoric (4000 B.C.-A.D. 43) and British Historical (43 A.D.-present day) sites. The questions were primarily structured around the assessment of bacterial bioerosion of bone, although several measures of bone diagenesis were used in order to better understand how these changes might be used in unison to reconstruct early taphonomic histories of archaeological bone samples. Samples of bone from European Later Prehistoric and British Historical archaeological sites were compared, as these assemblages represented the best possible proxies of differential funerary treatment. The religiosity associated with Historical periods, as well as the articulated state of most of skeletons, meant that it could be assumed that the majority of remains recovered from British Historical cemeteries had been buried soon after death. The exact funerary treatment afforded to individuals recovered from the European Later Prehistoric sites was unknown, although there was ample archaeological evidence that bodies had been treated in diverse ways which differed from the consistent processes practised during the British Historical periods (Darvill 2010). The research questions were addressed by investigating the nature of differences in several measures of diagenesis between bone samples from Historical and Later Prehistoric phases. A number of factors that may have enacted an influence on bone diagenesis were considered during this analysis in order to control for their potential effects, although it should be emphasised that the main aim of this study was to assess how far funerary treatment impacted on variation in bone diagenesis, rather than account for all variation in measures of diagenetic change.

The analysis expounded above relied upon the variation between the funerary treatments that were practised in British Historical and European Later Prehistoric periods. However no assumptions were made or were required regarding the exact treatment of the Later Prehistoric remains, other than the processes employed did not always involve immediate

inhumation. Therefore, the results of the primary analysis were combined with forensic studies of cadaveric decomposition to produce interpretations of funerary treatment based on the diagenetic and taphonomic evidence from each Later Prehistoric site. These studies provided examples of the ways in which measures of bone diagenesis may be used in reconstructions of funerary treatment practised in the past.

1.2 STRUCTURE OF THESIS

This thesis is divided into eight further chapters and two Appendices. The Background chapter provides more detailed discussion of bone microstructure and diagenetic processes, particularly bacterial bioerosion. The discussion of bioerosion includes justifications for the assumption of its bacterial and endogenous origin. The Background chapter also addresses the different factors that enact an influence on bodily putrefaction and provides some reasoning as to why it was thought that particular funerary rites would predominantly influence measures of bone diagenesis.

The Methodology chapter provides descriptions of the techniques used in the microstructural analysis of the archaeological bone samples. The details of the variables recorded for each bone sample, as well as the justification for their inclusion, are also discussed in this chapter. These variables included measures of bone diagenesis as well as factors that may have influenced diagenetic change. The Materials chapter provides a discussion of the sites whose human remains were included in the current study. Each description discusses the site background as well as taphonomic and environmental information that was relevant to the diagenetic analysis of each site assemblage. The sampling methods had to be adapted to each site. Detailed descriptions of the sampling strategies employed for each site assemblage are also explained in the Materials chapter.

The results are split into two chapters. The first is comprised of the systematic statistical testing of variation in each diagenetic parameter across the whole sample of remains (Primary Analysis). The second results chapter presents results from discrete and supplementary assemblages, which were used to reinforce the findings from the Primary Analysis and provide data for interpretations of site-specific patterns of bone diagenesis. The Discussion chapter presents an amalgamation and interpretation of both results chapters. Discussions of these interpretations are used to directly address the research question. The Specific Discussion

chapter is composed of exemplary site-specific interpretations of diagenetic and taphonomic information in terms of early *post mortem* processes, based upon the conclusions of the Discussion chapter. These reports provide examples of how measures of bone diagenesis may be used in reconstructions of funerary treatment at archaeological sites. The final Conclusion chapter presents a summary of all findings and how they answered the research questions. These conclusions are qualified by discussions of the current study's limitations. Consideration of the results and their limitations leads to a discussion of recommendations for future research directions.

Throughout the thesis 'Image' refers to an unmodified photo or micrographs. 'Figure' represents an illustration or an illustrated photo/micrograph. Binary and Ordinal Logistic Regression models constituted the core statistical tests used in the Primary Analysis. These models produced a lot of information, some of which was not directly relevant to the current study. Relevant information is summarised in the main text. Appendix 1 consists of IBM SPSS tables of extraneous results from ordinal and binary logistic regression models. The second Appendix 2 presents a table of results from all the statistical tests that were conducted. This table illustrates the Holm-Bonferroni method of correcting for multiplicity as applied to the statistical outcomes produced as part of the current research.

2 BACKGROUND

This chapter will provide background information on the basic microstructure of bone and bone diagenesis. The discussion of bone microstructures is pertinent to this thesis, as they dictate the progression of certain types of bone diagenesis and will be used as points of reference. The link between early taphonomy of a body and bone bioerosion is based upon the notion that the osteolytic microorganisms originate within the organism itself and are active during the putrefaction stage of bodily decomposition (Child 1995a, Bell *et al.* 1996; Jans *et al.* 2004; Nielsen-Marsh *et al.* 2007; Hollund *et al.* 2012). The second part of this chapter will provide a discussion of bone diagenesis, particularly the various forms of bioerosion. This section will also examine the evidence that bacterial bone bioerosion is propagated by endogenous rather than exogenous microorganisms.

Cadaveric putrefaction is affected by a large range of variables (Rodriguez & Bass 1983; 1985; Campobasso *et al.* 2001; Vass 2011). The third part of the chapter will discuss the factors that can influence bodily decomposition and provide reasoning as to why bone bioerosion is likely to be linked to certain specific funerary processes. This part of the chapter will also discuss how the link between putrefaction and bone bioerosion might be useful in addressing archaeological problems. The final part of this chapter discusses the aims and objectives as well as the research strategy that was adopted by the present study.

2.1 BONE MICROSTRUCTURE

Bone is a specialised form of calcified collagen (carbonated hydroxyapatite). The mineral phase consists of a crystalline lattice of calcium and phosphate (calcium hydroxyapatite) that includes occasional substituted ions such as fluoride (Junqueira *et al.* 1986). Collagen, a fibrous group of proteins consisting mainly of glycine, proline and hydroxyproline, constitutes the majority of the organic phase (Junqueira *et al.* 1986). Non-collagenous proteins such as osteocalcin and albumin make up the remainder of the protein fraction (Child 1995a; Cattaneo *et al.* 1995; Collins *et al.* 2002; Cappellini *et al.* 2011).

The intimate bond between the inorganic and organic osseous phases is not well understood, but it is directly related to the unique biomechanical properties that are crucial to a bone's functionality within the musculo-skeletal system. The strength of the mineral-protein bond is

responsible for the persistence of bone over archaeological timescales (Maximow & Bloom 1957). Removal of the mineral phase produces a softer substance that cannot retain a rigid form whereas absence of the organic collagen leaves a hard but brittle scaffold (Junqueira *et al.* 1986: 146). The combination of the two phases produces a plastic substance that is strong and adaptable to stress (Maximow & Bloom 1957).

Histology is the study of the microscopic anatomy of plant and animal tissue. The gross internal structure of bone (histomorphology) can vary across anatomical parts and species, but the development and organisation of the bone microstructure remains consistent. Several types of microstructures exist within bone. The frequency of their appearance differs depending on the age and development of the organism (Junqueira *et al.* 1986) (Image 2.1).

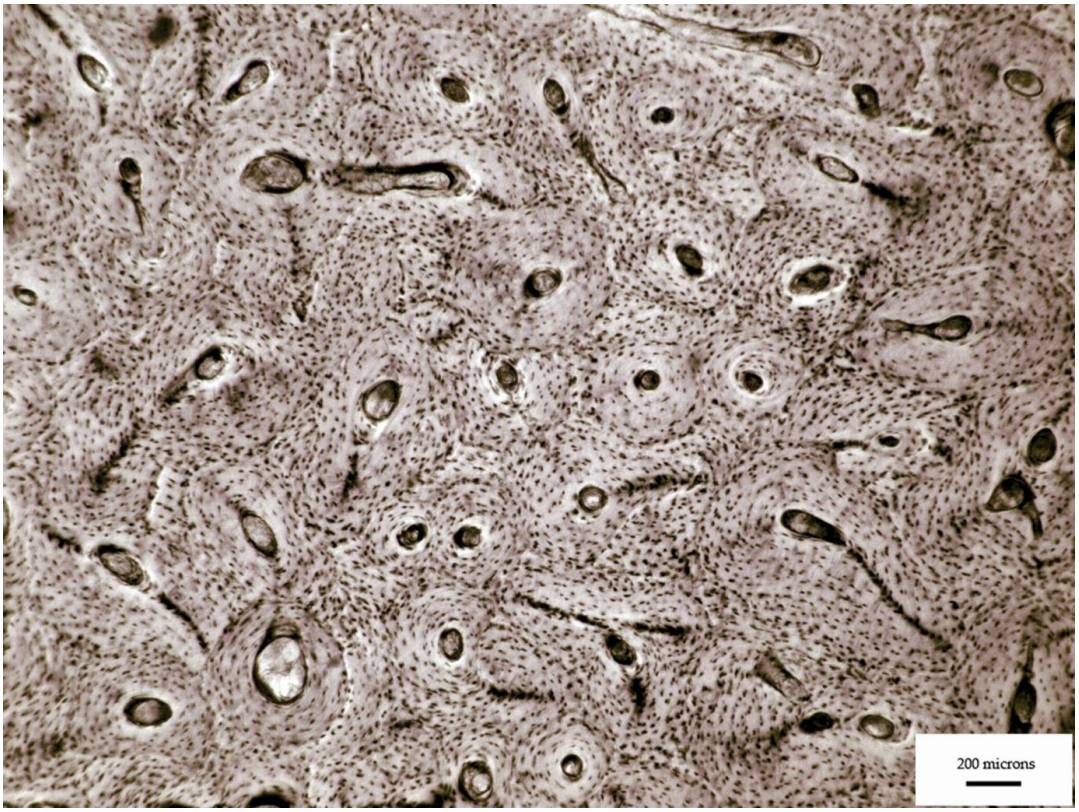

Image 2.1: Micrograph of a transverse thin section of femoral bone from a dissected human cadaver demonstrating healthy organised secondary bone microstructure (taken by the author).

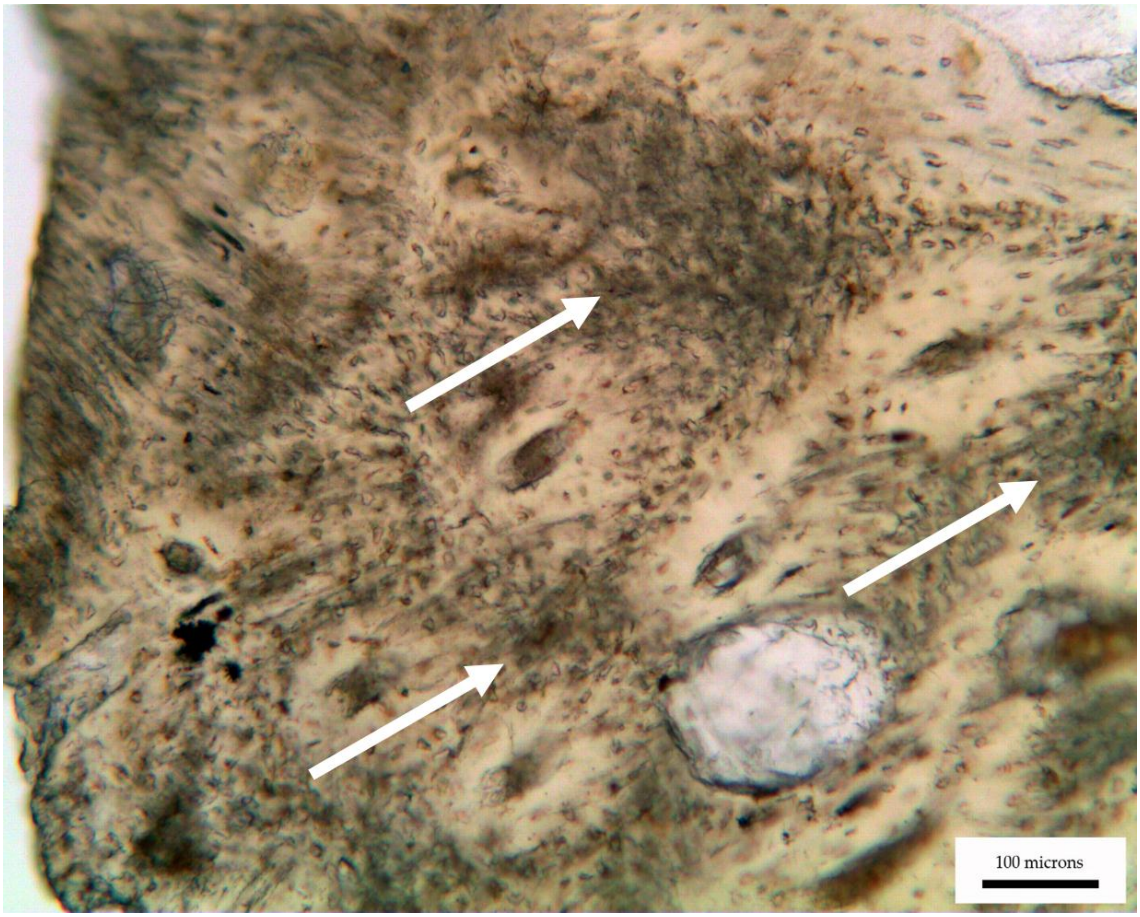

Image 2.2: Micrograph of an archaeological infant femoral transverse thin section. Disorganised randomly-orientated collagen fibres produce woven bone structures which can be observed within the grey areas (white arrows) (taken by the author).

The first type of bone tissue to appear in developing humans is woven bone, which consists of irregular organisations of collagen fibrils (Junqueira *et al.* 1986) (Image 2.2). Woven bone provides the scaffold for secondary bone formation and is characteristic of neonatal skeletons (Junqueira *et al.* 1986). This temporary microarchitecture is gradually replaced by secondary mineralised structures that consist of organised parallel collagen fibres 3-7microns thick. These fibres can take three different forms: circumferential lamellar bone, sub-circular (osteonal) lamellae or parallel interstitial lamellae (Figure 2.1). Marginal circumferential lamellar bone is found at the cortical surface (periosteal surface) and towards the medullary cavity (endosteal surface). Haversian canals are produced when lamellar collagen fibrils form around blood vessels that travel longitudinally through the bone microstructure (Maximow & Bloom 1957).

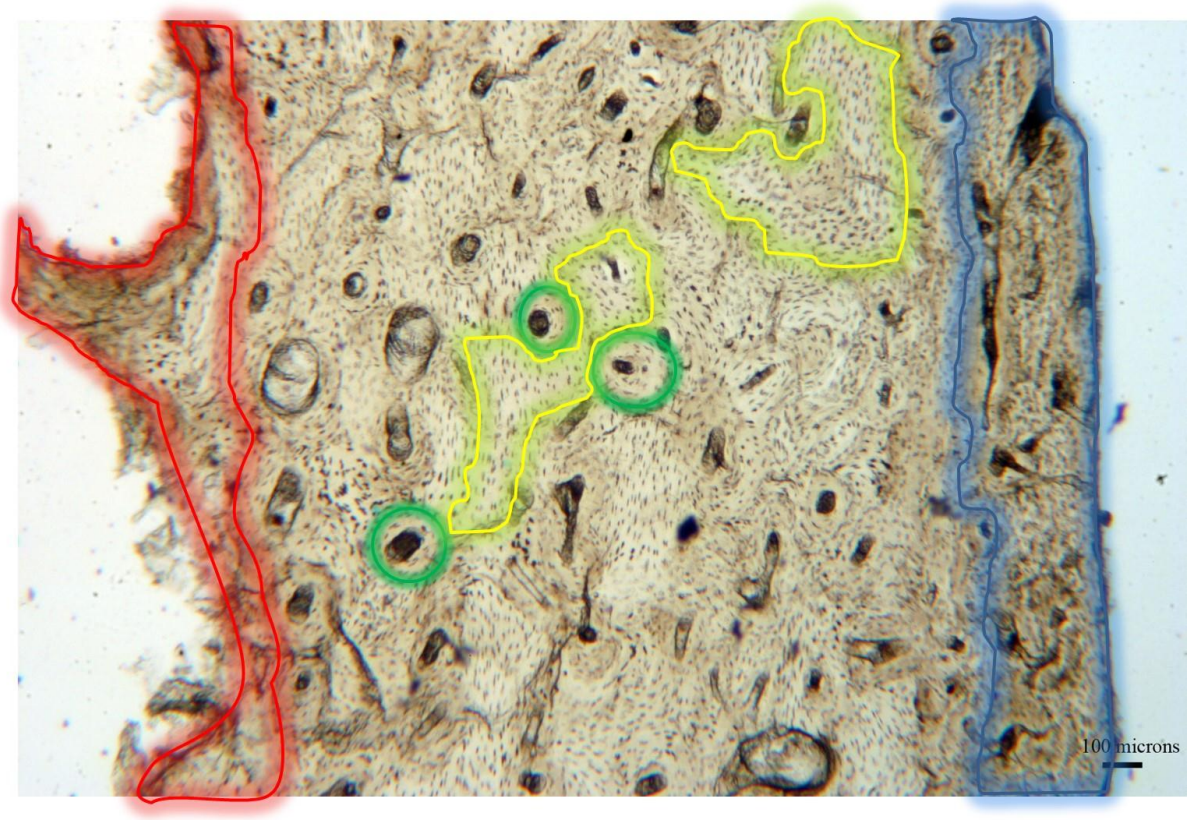

Figure 2.1: Micrograph of a modern adult human femoral transverse thin section. The different types of secondary bone organisation are highlighted: periosteal circumferential lamellar (blue), endosteal circumferential lamellar (red), Haversian or osteonal (green) and interstitial (yellow).

The Haversian canal combined with the circling collagen lamellae are referred to as a Haversian system or osteon (Maximow & Bloom 1957) (Figure 2.2). The margin of an osteon is defined by a mineralised barrier called a cement or reversal line. A cement line also surrounds the borders of the Haversian canals. Haversian canals are connected to one another, to the medullary cavity and to the periosteum via Volkmann's canals that travel transversely through the bone microstructure (Junqueira *et al.* 1986). Parallel interstitial bone is made up of primary collagen fibrils that have persisted in areas of bone that have not been replaced by Haversian systems. Interstitial bone can also consist of the remnants of Haversian systems that have been replaced by secondary and tertiary forms.

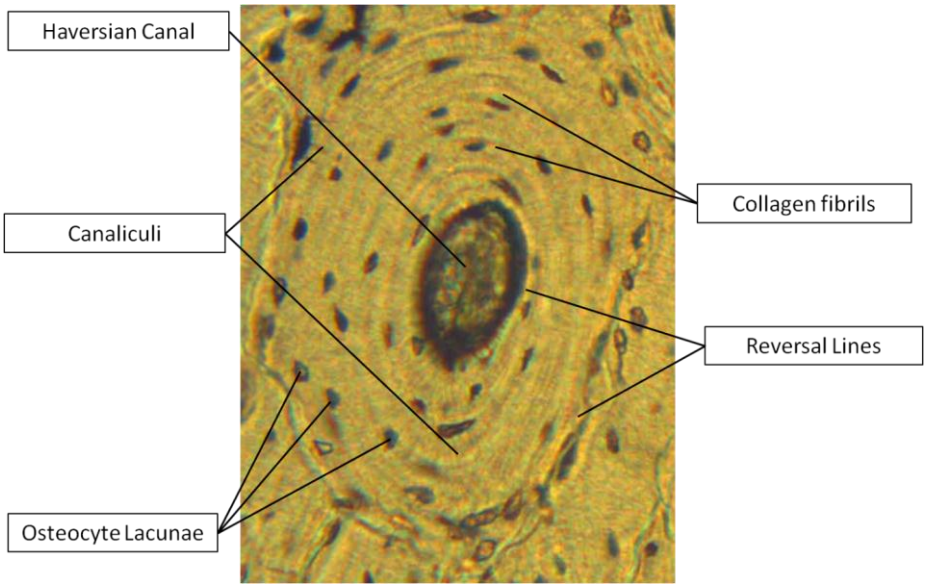

Figure 2.2: Anatomy of an osteon in a transverse plane.

Bone is an active tissue and is constantly undergoing internal remodelling in response to stress (Junqueira *et al.* 1986). Osteon formation is indicative of bone remodelling, as activity-related change to the bone microstructure requires vascularisation to supply nutrients to the active cells (Maximow & Bloom 1957). Osteons are only found within the dense cortical bone as the trabecular bone is supplied with nutrients by the marrow that lies within the large cavities that define its structure (Maximow & Bloom 1957). The constant remodelling of the internal bone microstructure means that the number of osteons contained within the internal bone microstructure increases cumulatively with age of an organism, to the detriment of circumferential lamellar and interstitial bone (Kerley 1965) (Figure 2.3). However, circumferential lamellar structures persist at the periosteal and endosteal margins regardless of age of an organism (Kerley 1965). Remodelling and secondary osteon formation is highest during adolescence and slows once an individual reaches adulthood (Junqueira *et al.* 1986). New Haversian systems that form during bone remodelling replace the whole or parts of older structures. Most osteons are not replaced entirely and fragments are often left over. Therefore the bone microstructure becomes increasingly compact with age. Younger osteons tend to be smaller in diameter than their predecessors due to structural pressures from osteon crowding limiting their size.

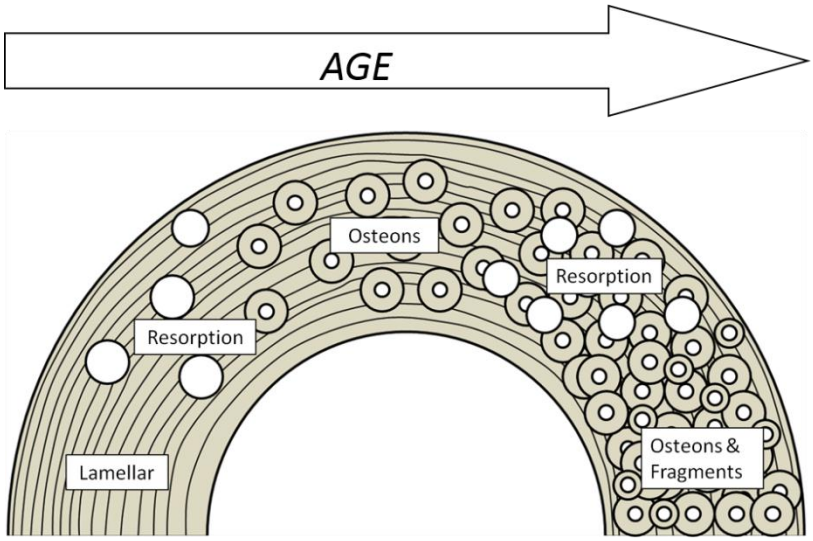

Figure 2.3: Schematic diagram of the change in microstructural organisation of bone due to cumulative remodelling over an individual's lifetime (redrawn from Kerley 1965: 153).

Bone remodelling is driven by cells specific to osseous materials. Osteoclasts resorb old bone by excreting acidic metabolites and collagenase. Acidic metabolites break down bone mineral. Collagenases are proteases adapted to breaking down collagen in spite of the molecule's tight helical binding (Junqueira *et al.* 1986; Child 1995a). Osteoclasts produce and occupy scalloped resorptive bays within the bone matrix named Howship's lacunae (Junqueira *et al.* 1986). Osteoblasts secrete collagen to form new lamellar bone structures. Osteoblasts eventually surround themselves with bone and become trapped within the matrix. These trapped cells are called osteocytes and the small (22-52microns diameter) cavities they produce within the bone matrix are referred to as osteocyte lacunae (Junqueira *et al.* 1986). The role of osteocytes in bone formation ensures that they follow the contours of the lamellar bone and appear to orbit the Haversian canal within osteons. Osteocytes are connected to one another and the Haversian canals by networks of fine meandering canaliculi. In areas of microstructure where bone remodelling is infrequent, the osteocyte cell can die leading to the ossification of the lacuna (Garland *et al.* 1988; Schultz 1997).

All microscopic bone structures can be viewed using thin section normal transmitted light microscopy or polished thick section Scanning Electron Microscopy (SEM) and Transmission Scanning Electron Microscopy (TEM) (Cook *et al.* 1962; Stout 1978; Turner-Walker & Syversen 2002; Jans 2008). Bone collagen fibres are orientated at 90° to one another (Junqueira *et al.* 1986; Schultz 1997). This pattern of orientation means that adjacent collagen fibres refract light at perpendicular planes (Schultz 1997). The organisation causes the collagen matrix to

appear birefringent when examined under polarised light (Junqueira *et al.* 1986; Schultz 1997) (Image 2.3). The birefringence forms a characteristic 'Maltese Cross' pattern within osteons (Hackett 1981) (Image 2.4).

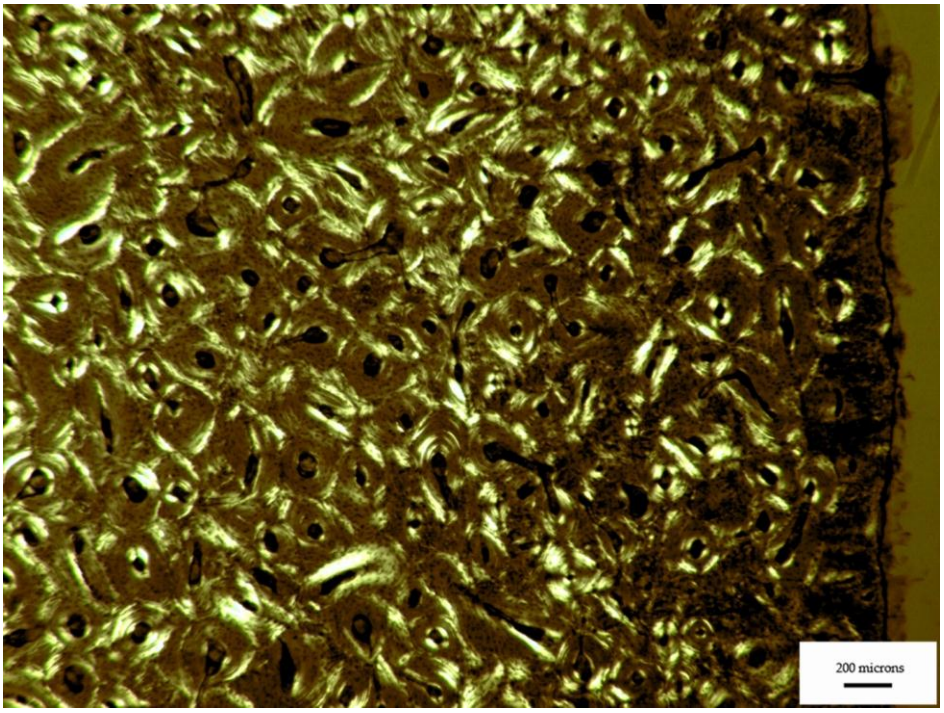

Image 2.3: Micrograph of a transverse thin sections of a modern fresh adult femur demonstrating collagen birefringence under polarised light (taken by the author).

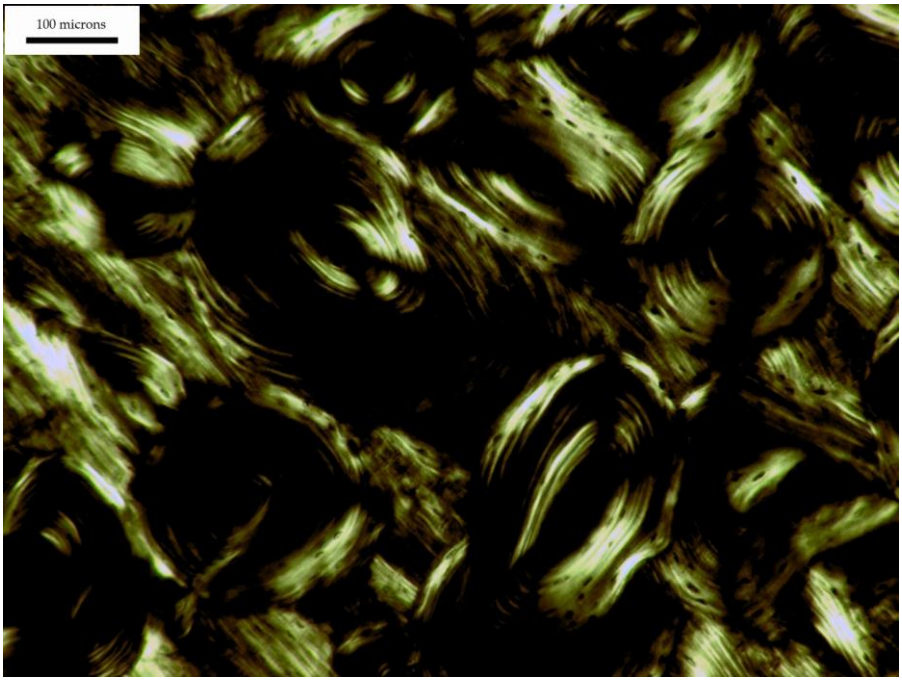

Image 2.4: Micrograph of a transverse thin section of a modern fresh adult femur under polarised light. The Maltese cross pattern of collagen birefringence can be observed surrounding osteons (taken by the author).

2.2 BONE DIAGENESIS

Diagenesis is a geological term that refers to the chemical and physical changes that sediment undergoes that lead to its incorporation within the lithosphere (Lee-Thorp & Sealy 2008). This term has been adapted by archaeological disciplines to describe the post-depositional physical and chemical changes archaeological remains undergo through interactions with their burial environment (Wilson & Pollard 2002). Diagenesis of archaeological artefacts has two possible endpoints: incorporation of the artefact into the lithosphere (fossilisation) or destruction (Wilson & Pollard 2002). Bone diagenesis refers to any physical and chemical process that encourages the degradation of bone proteins and the simultaneous dissolution or replacement of the hydroxyapatite matrix (Hedges *et al.* 2005). Mineral dissolution will lead to complete bone disintegration, whereas mineral replacement will eventually produce a fossilised bone (Trueman & Martill 2002; Tuross 2002). Bone diagenesis does not begin at the point of burial, but is initiated with the death of the organism (Nielsen-Marsh & Hedges 2000; Nielsen-Marsh *et al.* 2007; Smith *et al.* 2007).

2.2.1 Measures of Diagenesis

The multi-factorial nature of bone diagenesis and the complexity of bone composition make it difficult to quantify whole diagenetic changes to bone using only one form of analysis (Hedges *et al.* 1995; Hedges 2002). Bone diagenesis is usually assessed using one or more 'diagenetic parameters' (Hedges *et al.* 1995: 201). A diagenetic parameter is defined as, 'a single measurable aspect of a bone sample which reflects the degree of diagenesis which the bone has recognisably undergone' (Hedges *et al.* 1995: 201). Some studies of bone diagenesis have used as many as ten diagenetic parameters (Nielsen-Marsh & Hedges 2000). These parameters measure alteration to the mineral and organic phases of bone, either separately or simultaneously.

Bone diagenesis also encompasses changes to the appearance of the bone microstructure that do not necessarily entail degradation. These sorts of changes usually involve the penetration of the bone microstructure by extraneous minerals (Garland 1987; Schultz 1997; Hanson & Cain 2007). Interactions between the bone and the external environment can lead to localised discolouration of bone microstructure and the accumulation of foreign elements within bone porosities and microstructures (Garland 1987; Schultz 1997; Hanson & Cain 2007). Certain

measures of bone degradation can be used to recognise these features, although accurate identification of their composition is not possible with all techniques of analysis (Hollund *et al.* 2012).

2.2.1.1 Histological integrity

The diagenetic parameter that is utilised most often in studies of microscopic bone degradation is histological integrity. Histological integrity is assessed through a visual appraisal of the extent to which the internal bone microstructure has been degraded or altered (Grupe & Dreses-Werringloer 1993; Hedges *et al.* 1995). Histological integrity is assessed by the microscopic examination of bone samples through thin section light microscopy, Transmission and Scanning Electron Microscopy, or Backscattered Scanning Electron Microscopy (TEM, SEM & BSEM) (Hedges *et al.* 1995; Bell & Jones 1991) (Image 2.5). Histological alteration of bone is characteristic and easily identifiable when compared to sections of unaltered fresh bone (Grupe & Dreses-Werringloer 1993). Thin section light microscopy involves examination of the bone using normal and polarised light. All forms of bone diagenesis lead to collagen loss, which causes a reduction or loss of birefringence under polarised light (Hackett 1981) (Image 2.6).

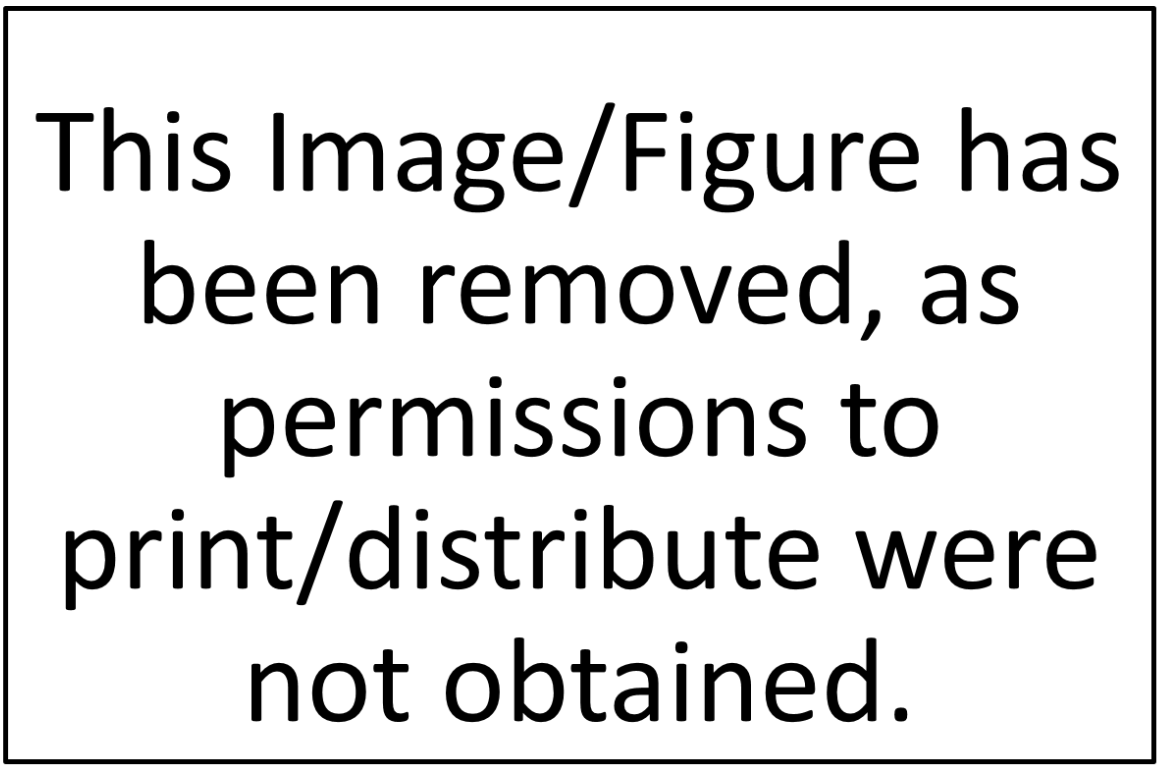

Image 2.5: Transverse BSE-SEM image of the endosteal surface of a Roman human ulna excavated from Castricum, The Netherlands. Arrow points to areas of bone that were analysed using SEM-EDS spot analysis to determine the constitution of exogenous infiltrations (Hollund et al. 2012: 8).

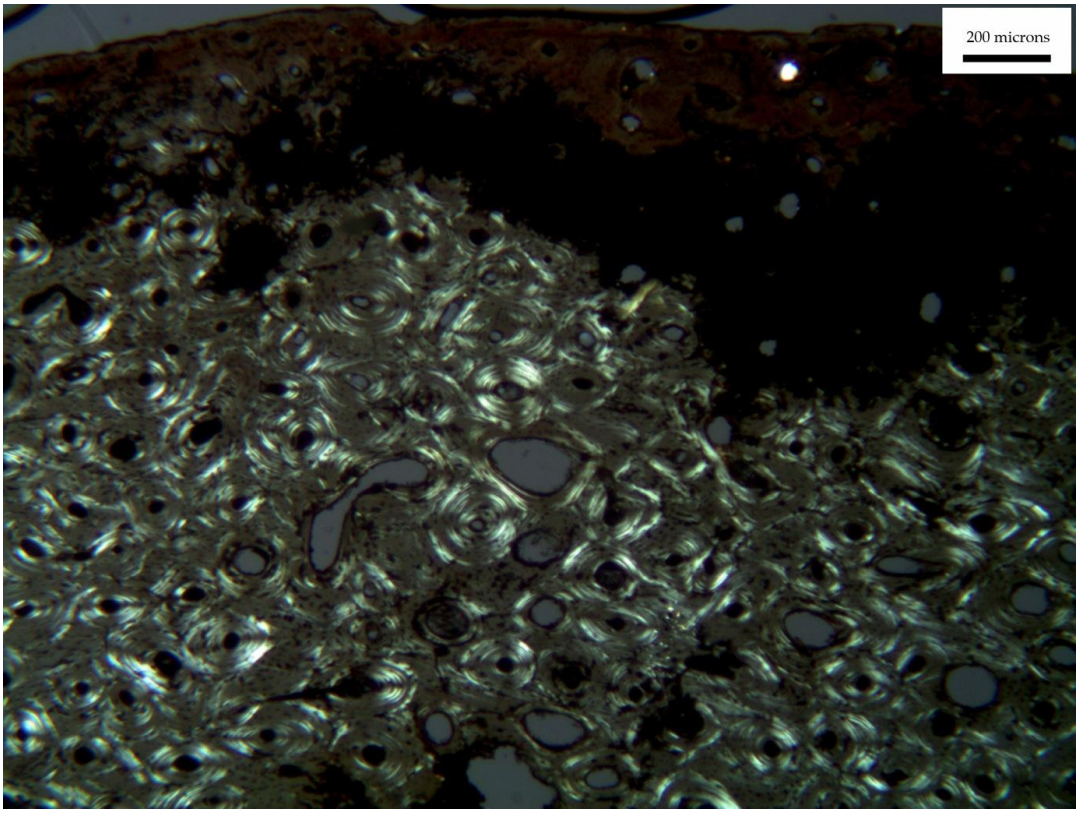

Image 2.6: Micrograph of a transverse archaeological human femoral thin section viewed under polarised light. Loss of collagen birefringence corresponds with histological degradation (taken by the author).

Histological destruction of bone correlates with measures of protein loss, such as biomolecular yield and can provide a rough guide as to the proportion of bone proteins that are likely to have survived into the archaeological record (Hagelburg *et al.* 1991; Hedges *et al.* 1995; Cipollaro *et al.* 1998; Götherström *et al.* 2002; Haynes *et al.* 2002; Rollo *et al.* 2002). The intimate bond between the organic and inorganic phases of bone guarantees that histological degradation will have involved some simultaneous alteration of the mineral, but changes to the mineral cannot be quantified directly through histological examination (Schoeninger *et al.* 1989; Hedges *et al.* 1995; Hedges 2002). Direct measures of mineral alteration correspond with histological alteration, but the precise relationship is complex (Hedges *et al.* 1995; Trueman *et al.* 2008). Histological assessment of bone is useful for documenting the extent and pattern of chemical or biological degradation of the microstructure and estimating protein loss (Hedges *et al.* 1995).

Qualitative features of bone diagenesis that can be recognised by histological examination include microfissures, staining, infiltrations and inclusions (Garland 1987). Microfissures are classified as breaks in the bone histology on the scale of an osteon. Microfissures have been

linked with a number of different influences including sample preparation techniques, sediment movement, acidic degradation, heat treatment and collagen hydrolysis (Garland 1987; Hanson & Buikstra 1987; Jans *et al.* 2002; Guarino *et al.* 2006; Turner-Walker & Jans 2008). Microfissures have been linked most often with diagenetic changes that promote bone shrinkage through loss of mass (Hanson & Cain 2007; Pijoan *et al.* 2011; Squires *et al.* 2011). Heating causes moisture within the bone proteins to evaporate (Hanson & Cain 2007; Pijoan *et al.* 2011; Squires *et al.* 2011). Acidic degradation removes bone mineral (Gordon & Buikstra 1981; Smith *et al.* 2007; Turner-Walker & Peacock 2008).

Histological staining refers to the discolouration of bone microstructure usually promoted by interactions with the external environment (Garland 1987; Shahack-Gross *et al.* 1997; Hanson & Cain 2007) (Image 2.8). Inclusions are defined as extraneous materials that have been deposited within natural bone microporosities, usually through mineral precipitation during groundwater percolation (Garland 1987; Garland *et al.* 1988; Grupe & Dreses-Werringloer 1993) (Image 2.9). Infiltrations consist of extraneous materials that lies within the bone matrix (Garland 1987; Grupe & Dreses-Werringloer 1993) (Image 2.10).

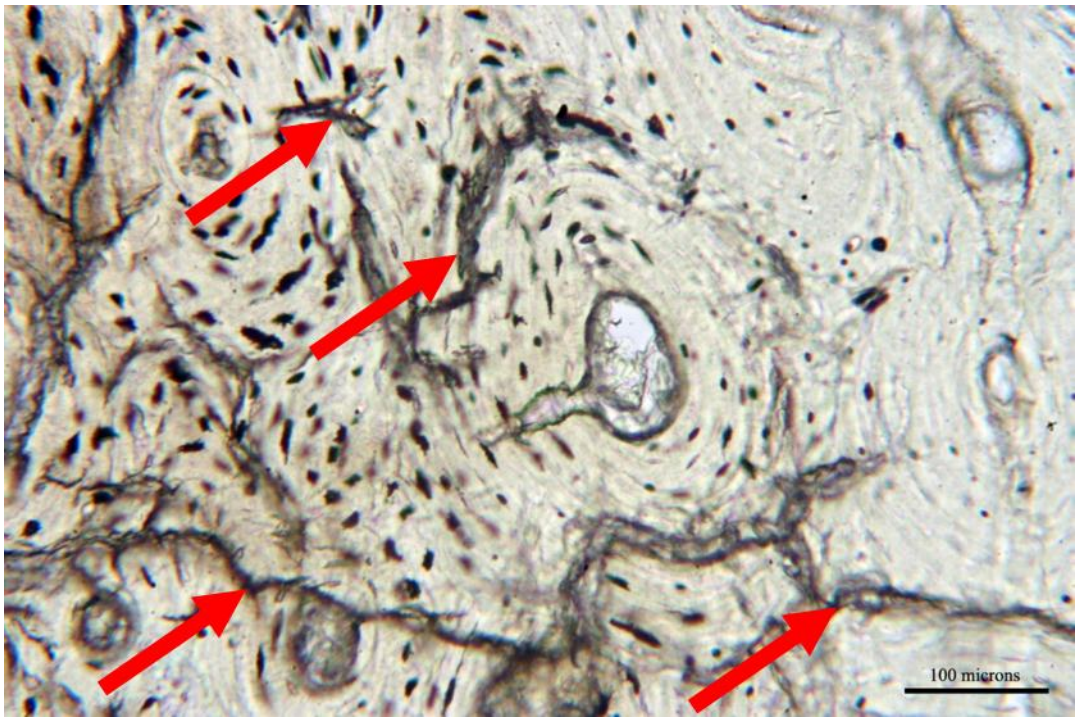

Image 2.7: Micrograph of an archaeological femoral transverse thin section. Microfissures can be observed surrounding the osteons (red arrows) (taken by the author).

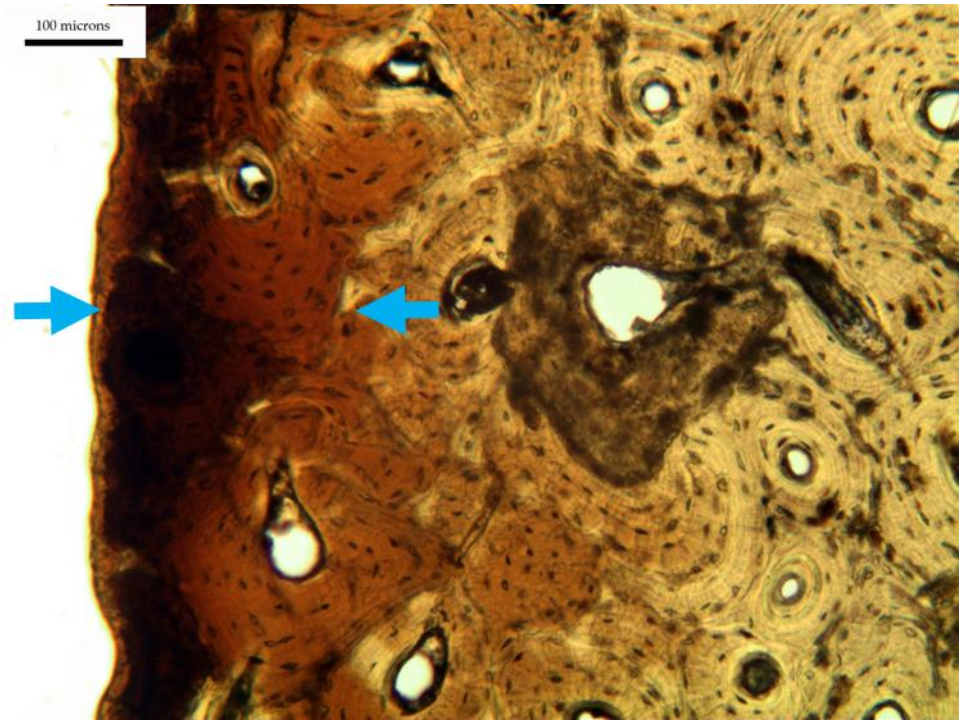

Image 2.8: Micrograph of a transverse thin section of an archaeological human femur demonstrating intense orange microstructural staining at the periosteal surface (between the blue arrows) (taken by the author).

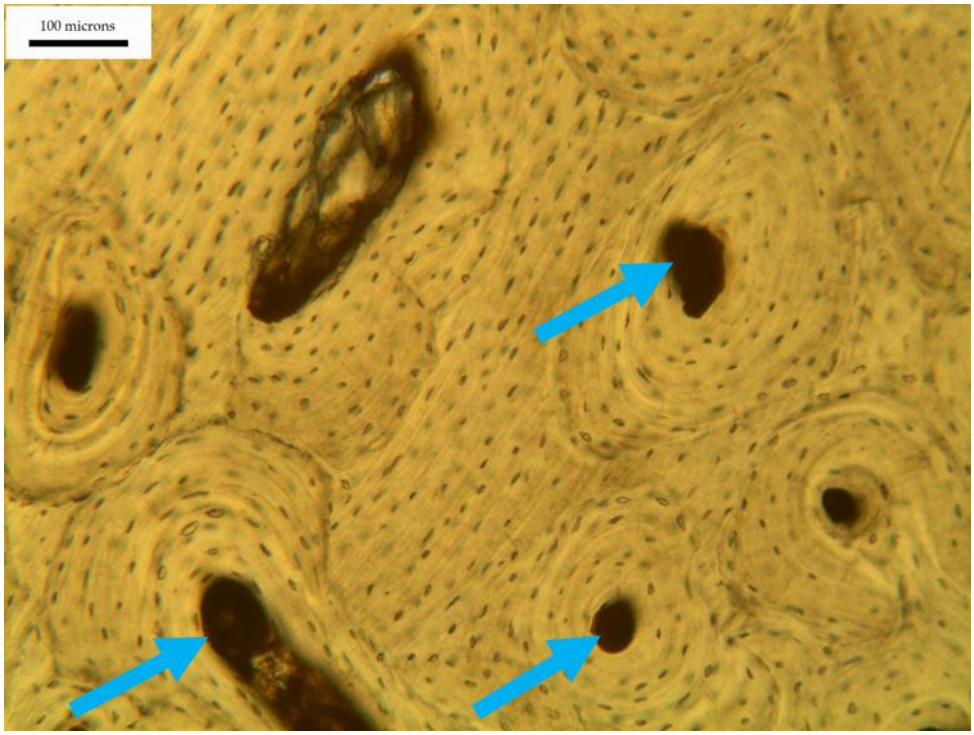

Image 2.9: Micrograph of an archaeological human femoral transverse thin section. Dark brown inclusions can be observed within the Haversian canals of osteons (blue arrows) (taken by the author).

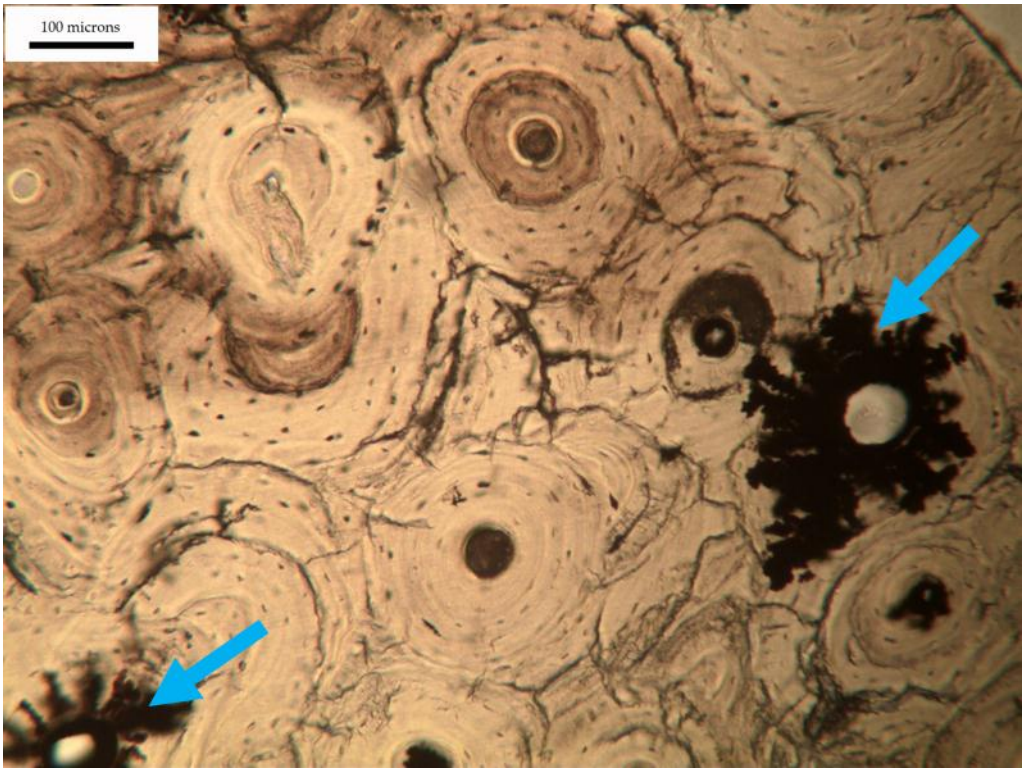

Image 2.10: Micrograph of an archaeological human femoral transverse thin section. Material that has infiltrated the bone matrix can be seen surrounding certain Haversian canals (blue arrows) (taken by the author).

2.2.1.2 Measures of Protein Content

There are several diagenetic parameters that directly measure the loss of organic bone content, such as percentage remaining carbon (%C), percentage remaining nitrogen (%N), C/N ratio or ancient DNA (aDNA) yield (Hedges *et al.* 1995; Colson *et al.* 1997; Götherström *et al.* 2002; Rollo *et al.* 2002; Smith *et al.* 2005 Devièse *et al.* 2010). Measurement of collagen loss has most often been calculated using the C/N ratio. There are several ways of measuring these parameters, but normally they involve the combustion or gelatinisation of a fraction of the bone sample followed by analysis in a mass spectrometer. Bones that demonstrate the highest levels of histological destruction often retain extractable amounts of organic molecules (Grupe 1995; Hedges *et al.* 1995; Balzer *et al.* 1997; Nicholson 1996).

It is possible that the degradation of bone protein gradually encourages collagen cross-linking via Maillard reactions. Cross-linking forms covalent bonds between organic polymer chains, creating substances that are more difficult to break down (Collins *et al.* 1995; Grupe 1995; Hedges *et al.* 1995; Balzer *et al.* 1997; Nicholson 1996). These chains can form through interactions between endogenous organic residues or with exogenous diagenetic substances

such as humic acids (van Klinken & Hedges 1995; Nicholson 1996). Most archaeological bones will retain at least small quantities organic molecules (Collins *et al.* 1995: 183).

2.2.1.3 Crystallinity

Crystallinity quantifies the extent to which the hydroxyapatite crystals of a bone sample have been altered from those of fresh bone (Schoeninger *et al.* 1989; Hedges *et al.* 1995). Fresh bone retains a relatively homogeneous distribution of crystal shapes and sizes (Piepenbrink 1986; 1989). Mechanisms of bone degradation all involve the dissolution of the inorganic fraction. After initial dissolution, the bone mineral precipitates rapidly into a more stable form. The distribution of crystal sizes after reprecipitation is heterogeneous. Heterogeneity of crystal forms increases with diagenesis as the hydroxyapatite is progressively dissolved and reprecipitated (Hedges *et al.* 1995). The character of the changes to the mineral phase is dependent upon the process that was responsible for diagenesis.

Crystallinity has most often been measured using Fourier Transform Infrared Spectroscopy (FTIR), which monitors the hydroxyapatite phosphate infrared absorption peaks (Sillen & Parkington 1996). Differently-sized mineral crystals will absorb the infrared light at divergent wavelengths and so the signature or splitting factor (SF) of severely altered mineral crystals will be dispersed over a wider range of wavelengths (Van Klinken & Hedges 1995). The SF is usually translated into a Crystallinity Index score that is used to compare samples (Reiche *et al.* 2003). Raman spectroscopy, a modified version of FTIR, can be used to simultaneously detect the abundance of collagen along with the extent of mineral alteration (King *et al.* 2011).

Bone crystallinity has also been measured using x-ray diffraction and scattering (Person *et al.* 1995; Hiller *et al.* 2004). X-rays are diffracted at different angles depending on the sizes and spaces between the bone mineral crystals. High energy x-rays are fired at a bone sample and their diffraction pattern is measured (Schoeninger 1989 *et al.*; Piepenbrink 1989). The advantage of x-ray diffraction methods is that they can be used to characterise crystal shape as well as size (Wess *et al.* 2001; Hiller *et al.* 2004; Hiller & Wess 2006). Different forms of diagenesis can produce variable imperfect crystalline forms, and so x-ray diffraction techniques may be able to detect subtle differences in diagenetic alteration that other methods might miss (Hiller & Wess 2006).

Changes in bone crystallinity do not often correlate with other diagenetic parameters and subsequently these measures are not good indicators of overall diagenetic change (Pucéat *et*

al. 2004; Trueman *et al.* 2008). Diagenetic processes that have a similar net effect on other parameters can affect crystallinity in variable ways (Smith *et al.* 2007). For instance, chemical and biological erosion of bone both promote loss of protein, but affect the mineral differently (Parker Pearson *et al.* 2005; Smith *et al.* 2007). Crystallinity can be useful in differentiating between diagenetic alterations by biological or chemical processes (Hiller & Wess 2006). Diagenetic increases in crystallinity become less linear with time, as more variables begin to exert an influence (Hiller & Wess 2006).

2.2.1.4 Microporosity

Diagenetic degradation always increases overall bone porosity, but different deleterious processes produce discrete pore sizes. The determination of overall and average pore volume (microporosity) can reveal the extent and nature of bone degradation (Nielsen-Marsh & Hedges 1999; Turner-Walker 1999). Mercury Intrusion Porosimetry (HgIP) is the technique that is typically employed to measure bone microporosity (Nielsen-Marsh & Hedges 1999; Turner-Walker 1999). This method measures the volume of bone that is taken up by pores of particular set sizes by forcing mercury into a sample under different pressures (Nielsen-Marsh & Hedges 1999). Each range of pressure can be related to specific pore sizes (Nielsen-Marsh & Hedges 1999). Initial studies focussed on measuring volumes of diagenetic macroporosity (pore radius ≥4nm) and natural bone microporosity (pore radius <4nm) (Hedges *et al.* 1995; Nielsen-Marsh & Hedges 1999). Diagenetic mineral dissolution and recrystallisation produces larger and more thermodynamically stable crystalline structures compared with fresh bone (Hedges *et al.* 1995). There is related growth in the size of the spaces between crystals, which increases macroscopic pore size (Hedges *et al.* 1995). Collagen and proteins within the bone are abundant in micropores and so their removal will reduce overall microporosity (Hedges *et al.* 1995).

Turner-Walker *et al.* (2002) and Smith *et al.* (2007) found that grouping microporosities into categories of small (>0.01 <0.1 microns), medium (>0.1 <8.5 microns) and large (>8.5 ~70 microns) increased their usefulness in studying diagenesis. Small microporosity represented diagenetically unaltered bone that retained a high collagen content, medium micropores were produced by microbial tunnelling (microbial spongiform porosity) and large microporosities reflected crystalline changes and collagen loss promoted by chemical bone dissolution (Turner-Walker *et al.* 2002; Nielsen-Marsh *et al.* 2007; Smith *et al.* 2007) (Image 2.11). Measures of

microporosity have been used to distinguish both the nature and extent of bone degradation. Microporosity is the only diagenetic parameter that has been found to correlate strongly with every other known measure of diagenesis, and so HgIP is regarded as the only method of diagenetic measurement that can singularly relay holistic information about microscopic bone alteration (Nielsen-Marsh & Hedges 1999; Jans *et al.* 2004; Nielsen-Marsh *et al.* 2007; Smith *et al.* 2007).

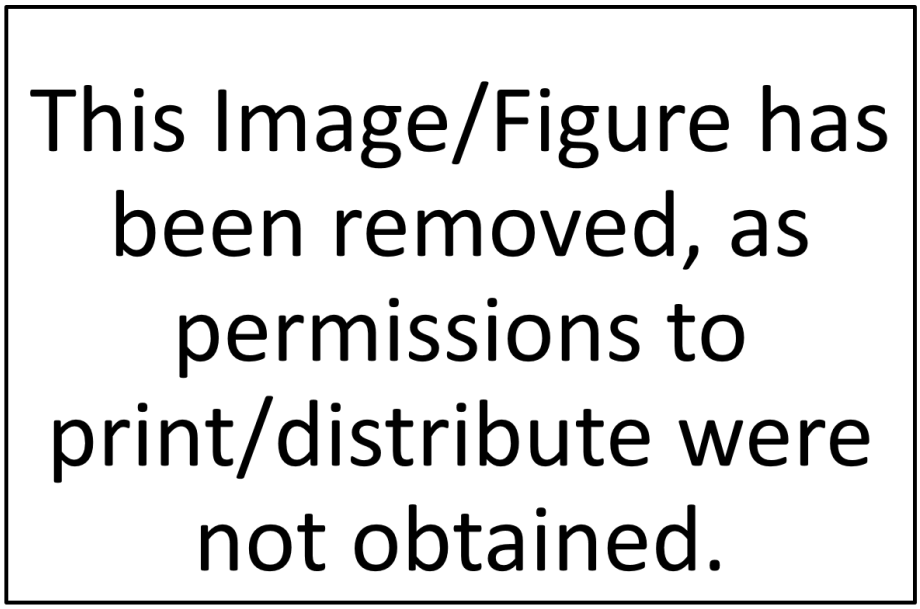

Image 2.11: SEM transverse image of microbial spongiform porosity within an archaeological human bone (Turner-Walker et al. 2002: 408).

2.2.2 Mechanisms of Diagenesis

There were initial fears that the complexity and variability of diagenetic processes would make it impossible to construct useful predictive models of bone degradation (Nielsen-Marsh & Hedges 2000; Nielsen-Marsh *et al.* 2007; Smith *et al.* 2007). However, studies that have investigated diagenesis within a wide variety of archaeological human and animal bone from the European Holocene identified only four diagenetic end-points (Nielsen-Marsh *et al.* 2007; Smith *et al.* 2007). Each of these end-points could be related to the influence of one of three different types of diagenetic degradation (Nielsen-Marsh *et al.* 2007; Smith *et al.* 2007).

2.2.2.1 Catastrophic Acidic Dissolution

Acidic burial environments have long been recognised as detrimental to the survival of bone over archaeological timescales (Gordon & Buikstra 1981; Bethel & Carver 1987). The destructiveness of an acidic environment is best demonstrated by the archaeological body stains that are sometimes recognised within acidic sands (Bethel & Carver 1987). Chemical degradation involves the breakdown of both the mineral and organic phases until the gross bone structure has completely disintegrated, leaving only traces of phosphate (Bethel & Carver 1987). The speed of bone destruction by acidic dissolution has ensured that diagenetic parameters have only characterised its early stages (Gordon & Buikstra 1981; Turner-Walker & Jans 2008; Turner-Walker & Peacock 2008; Turner-Walker 2012). The removal of mineral and protein increases the volume of bone represented by large microporosities as the bone dissolves (Turner-Walker *et al.* 2002). The chemical action transforms hydroxyapatite crystals into insoluble structures, which increases levels of crystallinity (Hedges *et al.* 1995). Early diffuse acidic demineralisation can be observed in histological bone sections as a graduated wave of collagen loss emanating from the periosteal edge and is often accompanied by enlarged canaliculi and osteocyte lacunae (Hanson & Buikstra 1987; Turner-Walker & Jans 2008) (Image 2.12). The damage to the bone microstructure and bone shrinkage that occurs as a result of the loss of bone volume causes microfissuring within affected areas of the bone histology. Subtle chemical alteration may not be visible microscopically, and can only be detected with measures of large porosity and localised crystallinity (Parker Pearson *et al.* 2005).

The circumstances that drive acidic dissolution can vary. The simplest scenario is that the groundwater and/or burial soil has a low pH (Gordon & Buikstra 1981). The bone is out of chemical equilibrium with its environment in these contexts and both the mineral and organic bone phases are dissolved and incorporated into the burial matrix (Gordon & Buikstra 1981; Bethel & Carver 1987). The rate of bone dissolution is dependent on the soil pH. Low pH will promote rapid deterioration that will continue until the bone has completely dissolved (Smith *et al.* 2007). If pH is close to neutral, the phosphate ions that are leached from the bone will buffer the external environment and slow or arrest mineral dissolution (Haynes *et al.* 2002).

Burials that are frequently recharged with fresh rainwater can also suffer chemical dissolution (Hedges & Millard 1995). If a body is interred within a free-draining context or an area with a high water table the bone will be subjected to cyclical wetting and drying events (Nielsen-Marsh & Hedges 2000; Pike *et al.* 2001). These processes will continually recharge the burial

context and reset the chemical equilibrium between the bone and its environment (Smith *et al.* 2007). The successive periods of intense chemical dissolution will eventually lead to the disintegration of the whole bone (Nielsen-Marsh & Hedges 2000; Smith *et al.* 2007). This effect is exacerbated by the acidity of rainwater.

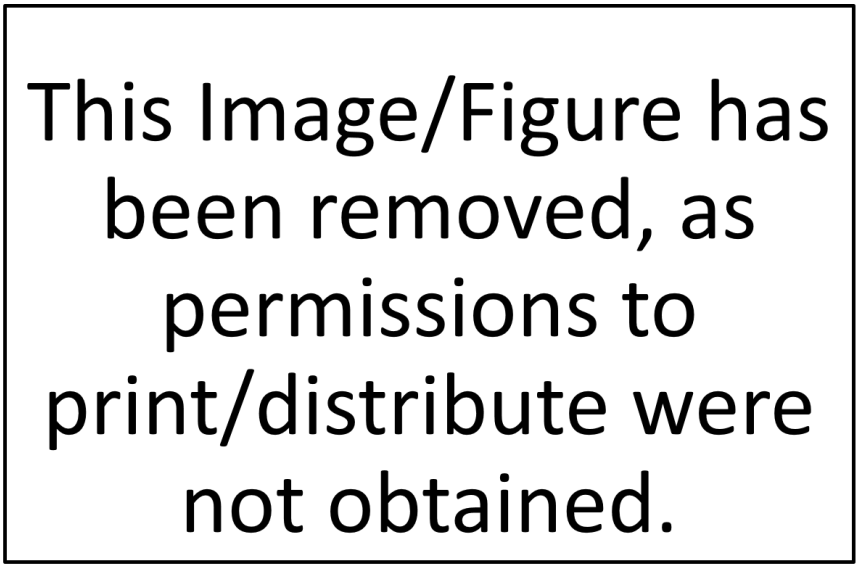

Image 2.12: BSEM image of the internal microstructure a cow metapodial that had been experimentally deposited within a sphagnum peat bog for four years. A diffuse wave of demineralisation can be observed radiating from the periosteal surface (Turner-Walker & Peacock 2008: 158).

Pike *et al.* (2001) modelled the net effect of particular hydrological regimes on bone dissolution: recharge, flow and diffusion dissolution. They found that rate of bone dissolution is constant under a diffusive regime, and accelerates with diffusion combined with recharge (Pike *et al.* 2001: 132). However, recharge dissolution is an uncommon phenomenon in the burial environment (Pike *et al.* 2001: 132). Flow dissolution rapidly destroys the bone but is limited by the amount of water available (Pike *et al.* 2001: 132). Dissolution by hydrological movement does not dissolve bone substantially in most burial environments (Pike *et al.* 2001).

2.2.2.2 Collagen Hydrolysis

Bone collagen slowly degrades through spontaneous hydrolytic chemical reactions with water in the environment (Collins *et al.* 1995). Hydrolysis causes the breakup of a target substance through the introduction of a water molecule that has split into hydrogen and hydroxyl constituents. The presence of water or hydrogen ions in any abundance within the bone or the

burial context will promote depolymerisation of collagen by hydrolysis of its peptide bonds (Collins *et al.* 1995). The polypeptide fragments of protein will continue to be degraded until the number of hydrogen bonds within the molecule drops below the minimum required, at which point the constituent elements dissolve out of the collagen mass (Collins *et al.* 1995: 177). These reactions will still take place, albeit at a reduced rate, when water is in limited supply (Collins *et al.* 1995: 181). Chemical collagen degradation alters bone crystallinity as a reciprocal effect of the disruption to the protein-mineral bond, but does not alter the overarching organisation of the internal microstructure (Smith *et al.* 2002; 2007). Bones that have been subjected solely to extensive collagen hydrolysis retain an immaculate histological structure. However, the loss of collagen will cause a reduction in fibril birefringence under polarised light (Hackett 1981). Loss of collagen also causes the volume of bone taken up by small microporosities to decrease as they are replaced by large diagenetic pores. The collagen loss can also be detected by measures of protein content. The alteration of the mineral phase caused by chemical hydrolysis can be distinguished by measures of crystallinity (Smith *et al.* 2007).

Collagen hydrolysis of bone proceeds too slowly in most depositional environments to have a significant diagenetic effect over archaeological timescales (Collins *et al.* 1995). Rapid processes such as chemical dissolution or biodeterioration will remove the majority of the bone collagen before collagen hydrolysis has made an impact (Smith *et al.* 2007). The protein loss and mineral alteration promoted by collagen hydrolysis may constitute a primary mechanism of bone fossilisation (Collins *et al.* 2002). Fossilised bone rarely shows evidence for extensive biological or acidic alteration (Trueman & Martill 2002; Tuross 2002). The prevention of these rapid diagenetic changes is likely to be a prerequisite for bone fossilisation (Trueman & Martill 2002; Tuross 2002; Smith *et al.* 2007). The rate of collagen hydrolysis is not linear. Residual collagen can be preserved through cross-linking (Collins *et al.* 1995).

Certain factors can accelerate collagen hydrolysis in exceptional circumstances (Image 2.13). Higher temperatures increase the rate of chemical reactions, causing more rapid breakdown of bone collagen (Collins *et al.* 1995). Boiling of bone mimics the effects of severe collagen hydrolysis (Roberts et al. 2002; Abdel-Maksoud 2010). In countries with temperate climates, most burial environments will not reach the critical temperatures required to significantly accelerate chemical collagen loss (Collins *et al.* 1995). Very alkaline soils might also encourage hydrolysis of collagen, as these contexts contain a heightened concentration of the hydrogen ions that catalyse peptide reactions (Smith *et al.* 2002; 2007). Most burial contexts do not

naturally reach the high pH levels that would significantly affect the rate of collagen hydrolysis (Smith *et al.* 2002).

The practice of adding slaked lime to a burial significantly increases the pH of a bone and its surrounding environment (Smith *et al.* 2002). This process could lead to artificial hydrolysis of collagen, and has been suggested as one explanation for the few prematurely fossilised or hydrolysed bones that have been found amongst some archaeological assemblages. Burial environments that expose the bone to intense wetting and drying cycles may also accelerate collagen hydrolysis (Smith *et al.* 2002).

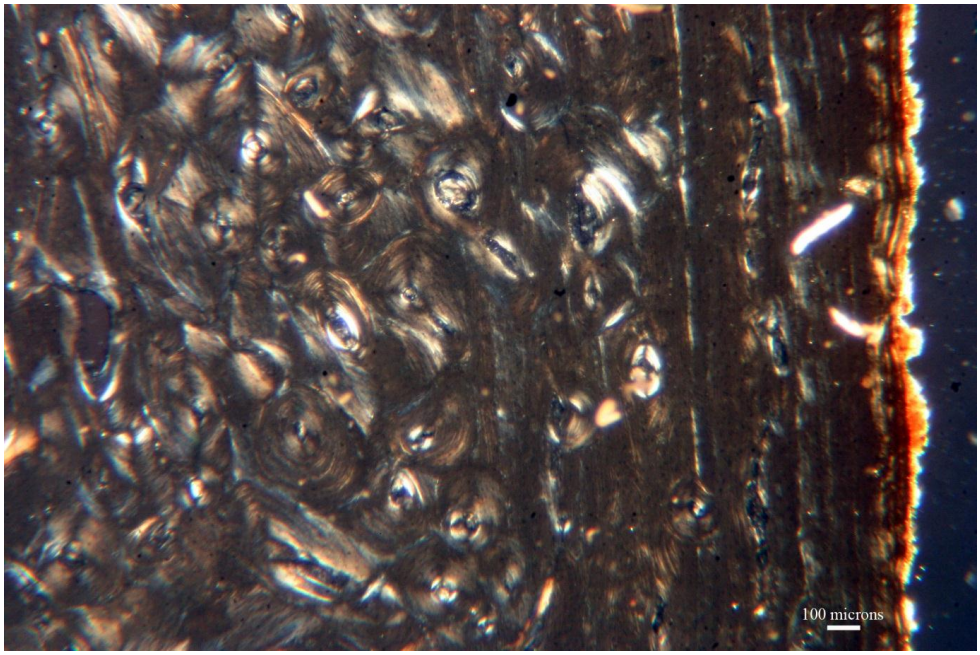

Image 2.13: Micrograph of a transverse femoral thin section of a Neolithic individual that was recovered from the site of Tell Halula, Syria viewed under polarised light. The specimen demonstrated excellent preservation of microstructures but reduced collagen birefringence, which indicated that bone protein must have been lost through chemical hydrolysis (taken by the author).

2.2.2.3 Bioerosion

The most common form of diagenetic alteration detected in archaeological bone is the regularised degradation and alteration of the composite bone structure by microorganisms, known as bioerosion. The loss of collagen and redeposition of the mineral by microorganisms produces discrete tunnels within the bone histology (Hackett 1981; Hedges *et al.* 1995; Turner-Walker *et al.* 2002). Microscopic tunnelling in the internal bone microstructure was first identified and attributed to the action of microorganisms by Wedl (1864). Bone that has been extensively bioeroded is characterised by high medium porosity, which corresponds with the

sizes of the tunnels produced by the microorganisms. There is a related loss of bone volume represented by small porosities as collagen content decreases. The dissolution and reprecipitation of the organic phase produces elevated crystallinity values. The removal of proteins by microorganisms can also be detected by measures of protein content (Hedges *et al.* 1995). Microbial tunnelling directly affects the microstructural organisation of the bone, and so measures of histological integrity and collagen birefringence are also affected (Smith *et al.* 2007; Nielsen-Marsh *et al.* 2007) (Image 2.14). These results vary with the intensity of biodeterioration. There has been some evidence to suggest that bone bioerosion occurs bimodally, either continuing to completion or not beginning at all (Hedges *et al.* 1995). However, numerous archaeological and experimental bone samples have been found to demonstrate intermediate levels of microbial attack (Davis 1997; Turner-Walker & Jans 2008; Fernández-Jalvo *et al.* 2010).

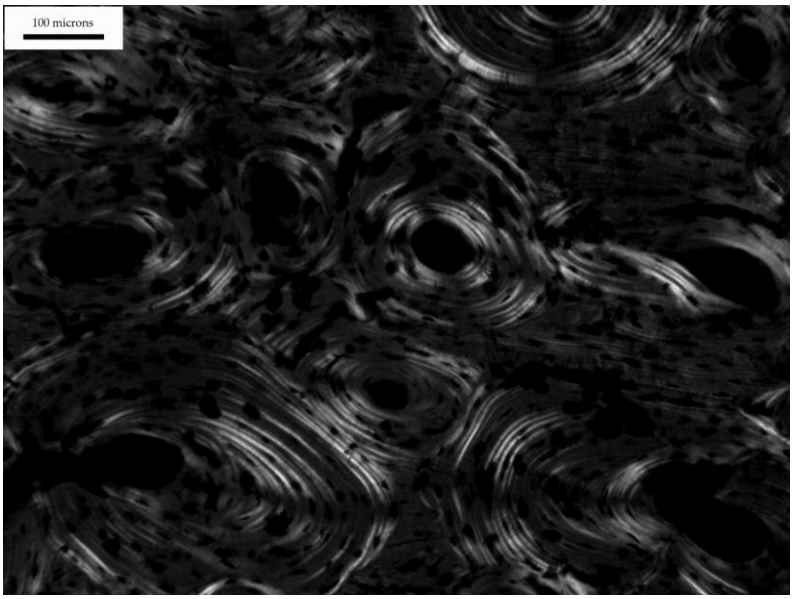

Image 2.14: Micrographs of a transverse femoral archaeological thin section viewed under polarised light. Bacterial tunnels can be observed to interfere with collagen birefringence (taken by the author).

Hackett (1981) was the first to describe the morphology of microbial tunnels or micro-foci of destruction (MFD) observed in archaeological bone. Hackett classified four morphological types: linear longitudinal, budded, lamellar and Wedl (Figure 2.4). The medium-sized microbial spongiform porosity defined by Turner-Walker *et al.* (2002) is produced by the Wedl-type lesions themselves. Within non-Wedl MFD, the medium porosities correspond with each lesion's internal porous structure (non-Wedl MFD) (Jans *et al.* 2002; Turner-Walker *et al.* 2002).

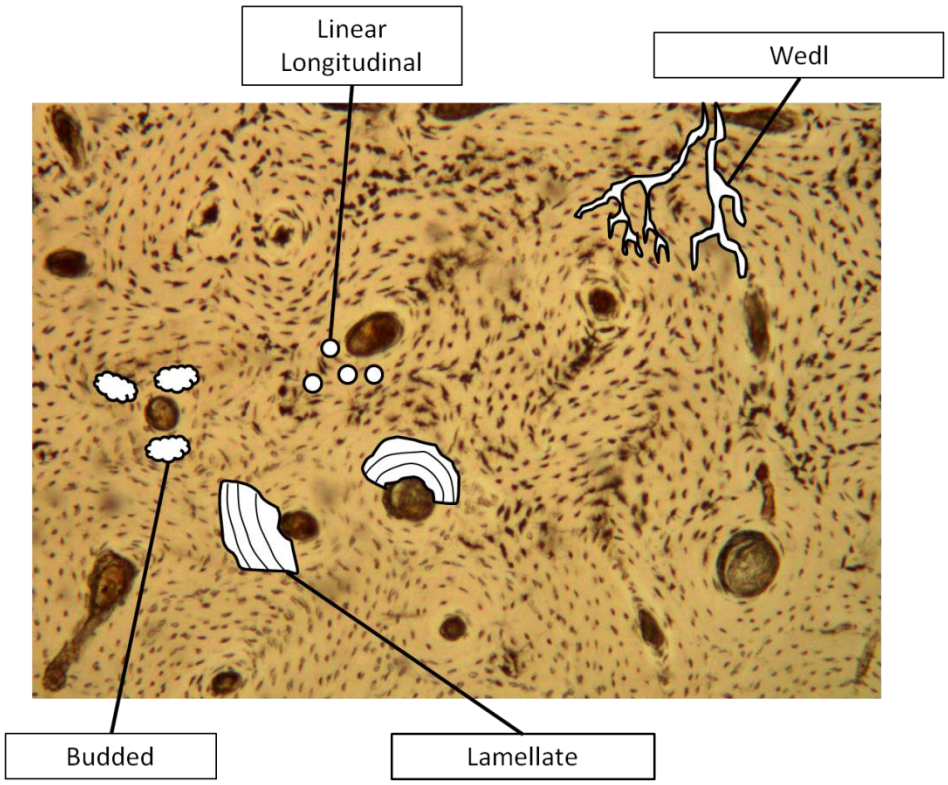

Figure 2.4: Schematic drawing of how different types of MFD appear within a transverse bone thin section (redrawn from Jans et al. 2004: 89).

The three types of non-Wedl MFD differ in their morphology but share similar characteristics (Hackett 1981). All three travel longitudinally through the bone and surround Haversian canals within osteons (Hackett 1981; Garland *et al.* 1988; Bell *et al.* 1996; Jans *et al.* 2004). Some studies report an initial association between non-Wedl MFD and enlarged osteocyte lacunae (Bell *et al.* 1996). Microorganisms may use these natural cavities to invade the bone microstructure to avoid the highly-mineralised cement lines that surround the Haversian canals (Bell 1990; Bell *et al.* 1996). Non-Wedl MFD are often limited by cement lines, which suggests that these boundaries are mineralised to a degree that renders them impenetrable to osteolytic bacteria (Hackett 1981; Balzer *et al.* 1997). The morphologies of non-Wedl MFD might be controlled by the bone microarchitecture (Bell 1990; Bell *et al.* 1996). Non-Wedl MFD are usually surrounded by a hypermineralised cuff or rim, which is formed when the mineral recrystallises after initial dissolution and transportation (Hackett 1981). Hypermineralised cuffs might only form if a bone's burial environment has a pH value within the 'recrystallization window' between pH 7.6 and 8.1 (Berna *et al.* 2004: 876).

The characteristics of non-Wedl MFD contrast with the centrifugal Wedl tunnelling, which is more often observed to penetrate the periosteal surface of the bone and travel transversely

through the microstructure (Hackett 1981; Marchiafava *et al.* 1974) (Image 2.15). Wedl tunnels do not follow the natural bone architecture and are not accompanied by hypermineralised rims (Hackett 1981). More recent studies have identified two further types of MFD. Type 2 Wedl tunnels resemble thinner versions of the Type 1 forms described above, and are usually observed spreading out from Haversian canals within osteons (Trueman & Martill 2002). External microscopic microbial channelling observed on cortical bone surfaces has been named Hackett tunnelling (Davis 1997).

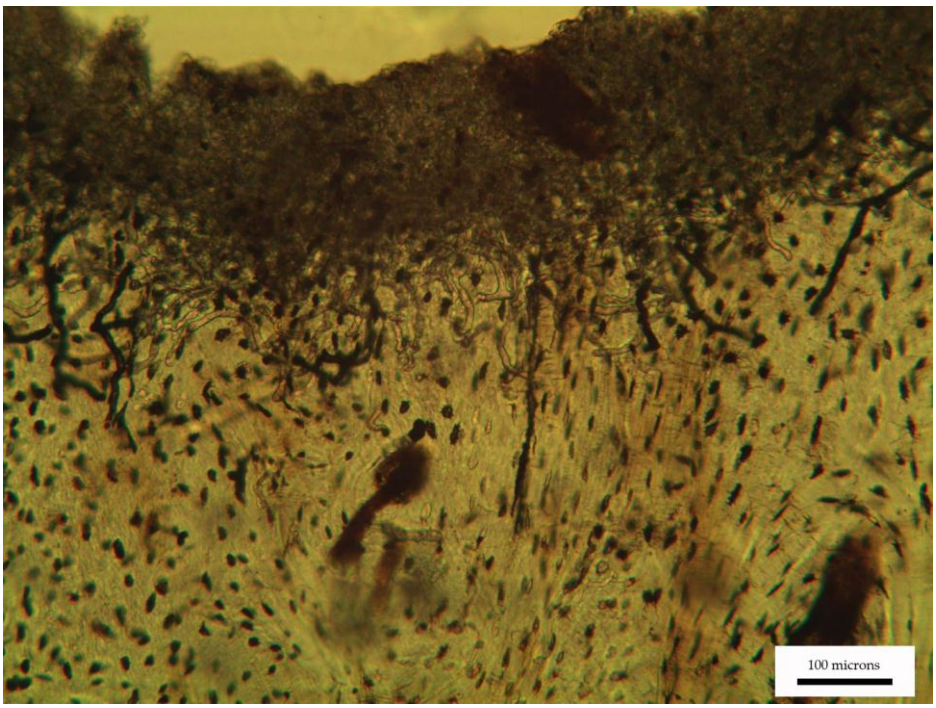

Image 2.15: Micrograph of a transverse thin section of an archaeological frontal bone that was recovered from the River Wye, near Bakewell. Wedl tunnelling can be seen radiating from the periosteal surface (taken by the author).

Non-Wedl MFD constitute the majority of microscopic biotic decay observed within archaeological bones (Jans *et al.* 2004; Nielsen-Marsh *et al.* 2007). It is difficult to say whether each form of non-Wedl MFD represents a distinct pathway of destruction relating to discrete organisms (Hackett 1981; Child 1995b). Coalesced groups of smaller forms of non-Wedl MFD, such as the linear longitudinal types, begin to resemble the larger budded and lamellar forms (Hanson & Buikstra 1987; White 2009) (Image 2.16).

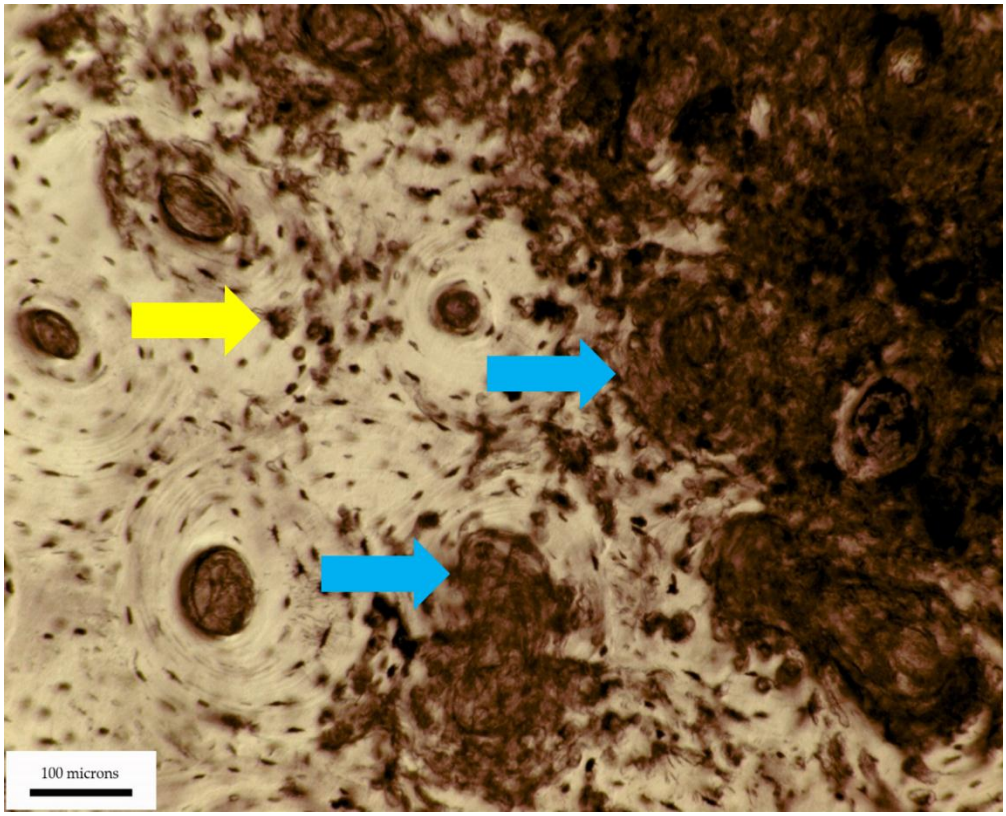

Image 2.16: Micrograph of an archaeological femoral transverse thin section. Non Wedl MFD can be seen in isolation (yellow arrows) and in coalescence (blue arrows) within different parts of the section. Coalescent smaller non-Wedl MFD begin to resemble the larger forms (taken by the author).

Most studies of bone diagenesis have emphasised that there is no correlation between the macroscopic and microscopic preservation of an archaeological bone (Hanson & Buikstra 1987; Bell *et al.* 2006; Hedges 2002; Jans *et al.* 2004; Guarino *et al.* 2006). Assessments of cortical preservation and whole bone fragmentation do not correlate with measures of internal diagenesis (Hedges *et al.* 1995; Jans *et al.* 2004; Jans 2008). The same studies have consistently failed to detect correlations between histological preservation and archaeological ages of specimens (Hedges *et al.* 1995; Hedges 2002; Jans *et al.* 2004; Nielsen-Marsh *et al.* 2007). A Bronze Age bone is just as likely to be histologically well-preserved as a medieval specimen (Trueman & Martill 2002; Jans *et al.* 2004; Nielsen-Marsh *et al.* 2007). The lack of correlation between bone bioerosion and archaeological time suggests that microbial attack to the internal bone microstructure completes within the first few decades after death (Hedges *et al.* 1995; Hedges 2002) (Image 2.17).

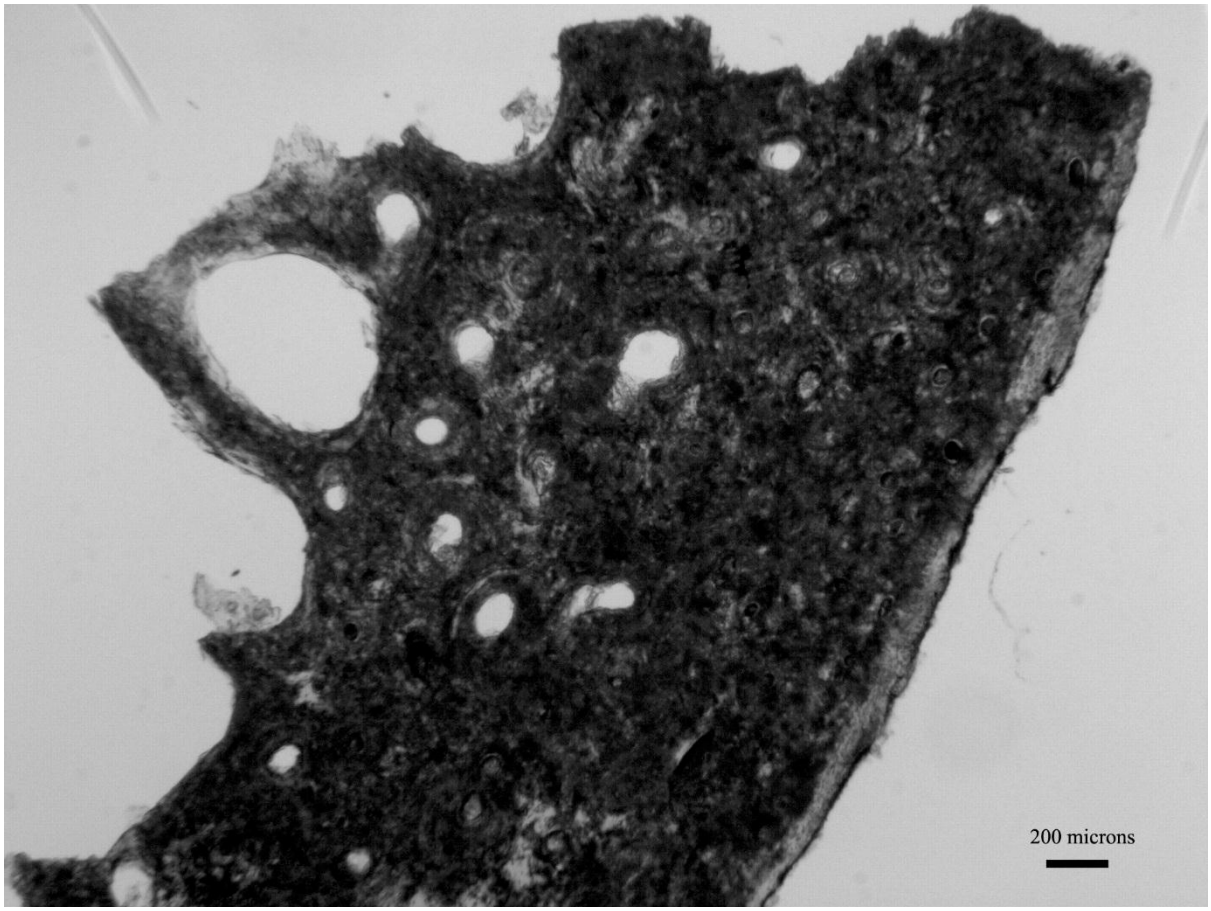

Image 2.17: Micrograph of a transverse thin section of an archaeological foot phalanx. The bone has been subjected to the maximal levels of bone bioerosion leaving slivers of preserved microstructure at the periosteal and endosteal peripheries (taken by the author).

2.2.3 Mechanisms & Origins of the Microbial Decomposition

The proposed link between bacterial bone bioerosion and funerary treatment is dependent upon the notion that the majority of bacteria responsible were endogenous to an organism and that the majority of bacterial tunnelling was formed during bodily putrefaction. The research and justification regarding the mechanisms and likely progenitors of internal bone bioerosion will therefore require some elaboration.

2.2.3.1 Mechanisms of Microbial Decomposition

The physical mechanisms of bone decomposition utilised by micro-organisms (fungi and bacteria) have not been observed directly (Child et al 1993; Child 1995a; 1995b). The likely processes involved have been constructed based upon the chemicals certain microbes are

known to produce, the environments in which they thrive, and the ways in which microorganisms are known to behave (Child *et al.* 1993; 1995a; 1995b). In order to break down a body's complex proteins, microorganisms need to be capable of producing proteases (Child 1995b). The collagen molecule is twisted into a highly stable left-handed triple helical structure that is highly adapted to resist enzymatic attack (Collins *et al.* 1995; Grupe 2001). In order to degrade this protein, microorganisms need to be capable of producing collagenase (Child 1995a; 1995b). Most species of bacteria excrete a protease, but only a minority can produce collagenase (Child 1995a). The bond between the collagen and the hydroxyapatite leaves only a small space within the molecular structure for extraneous substances to pass through (Mayer 1994; Nielsen-Marsh & Hedges 2000; Hedges 2002). Any molecule larger than water cannot fit through the gap (Child 1995a; 1995b; Nielsen-Marsh & Hedges 2000). Therefore the bone protein can only be accessed by collagenase enzymes after some dissolution of the mineral phase (Child 1995a; 1995b; Nielsen-Marsh & Hedges 2002; Hedges 2002).

Various species of fungi can invade and exploit the human body in life. Fungal organisms can infect the body's natural orifices causing metastatic infections and inflammation (Marchiafava *et al.* 1974). Fungal infection in living organisms rarely affects the bone (Marchiafava *et al.* 1974). Fungal hyphae are commonly found adhering to freshly excavated archaeological bone and have been observed to penetrate the bone via exposed vascular canals (Marchiafava *et al.* 1974; Hackett 1981). The cell walls of saprophytic fungal hyphae contain both proteolytic and collagenase enzymes, as well as acidic metabolites that promote bone mineral dissolution (Marchiafava *et al.* 1974; Piepenbrink 1986; 1989). Species of fungi that excrete metabolites can directly solubilise the mineral phase, although there is some debate as to whether they are capable of metabolising the resultant phosphate (Piepenbrink 1989). Marchiafava (1974: 207) suggested that attempts by fungi to ingest inorganic products of bone destruction will eventually result in poisoning and death. This view is supported by observations of dying hyphae surrounded by areas of bone dissolution within thin sections of bone (Marchiafava *et al.* 1974: 208). Fungal cell death results in the release of organic acids, which lowers the local pH and encourages bone mineral dissolution (Marchiafava *et al.* 1974: 208). The death of the preceding organisms may be the primary mechanism of mineral dissolution involved with fungal osteoclasia.

There is some debate as to whether most species of bacteria are able to produce acidic metabolites, and it has been suggested that bacteria cannot begin to degrade and exploit the bone collagen until there has been some localised removal of mineral (Hedges 2002). Certain bacteria may be facultative metabolite producers, which would explain why they are often not

observed to produce these substances *in vitro* (Grupe *et al.* 1993). The death of a bacterial organism and the subsequent release of organic acids can lower the pH or a microenvironment leading to the dissolution of the hydroxyapatite (Child 1995a). The proliferation of bacterial organisms through the internal bone structure may be dependent on the death of pioneer colonies (Child 1995a).

Child (1995a: 25) suggested that bone bioerosion by bacteria involves a complex interaction between obligate aerobes, obligate anaerobes and adaptive aerobes/anaerobes. Initial aerobic metabolism of amino acids leads to the production of carbon dioxide, water, nitrogen dioxide and sulphur dioxide. If this attack occurs rapidly, more oxygen will be consumed than enters the system. These processes will eventually produce an anaerobic environment. At this point, the obligate anaerobic and facultative anaerobic bacteria will take over protein decomposition via fermentation. This osteolytic action produces organic acids (Child 1995a). The organic acids will cause the pH of the localised micro-environment to drop, leading to the dissolution of the hydroxyapatite (Child 1995a). However, the lack of acidic metabolites will mean that this reaction will gradually slow and oxygen will diffuse back into the system, promoting the resumption of aerobic degradation (Child 1995a). Anaerobic decomposition facilitates rapid aerobic breakdown by dissolving the bone apatite, which would otherwise be impenetrable (Child 1995a). These two processes of microbial bone decay would be self-perpetuating.

This model still raises the question of how aerobic bacteria attain an initial 'foothold' in the bone matrix if they cannot independently degrade the hydroxyapatite (Nielsen-Marsh & Hedges 2000; Hedges. 2002). The initial demineralisation could be caused by deposition of the body within an acidic burial context or by hydration and recharge of the surrounding environment during heavy rainfall (Hedges 2002). However, all skeletons may be demineralised initially to some degree by the acidic organic products of early bodily decomposition and autolysis (Janaway 1987; Janaway 1996; Child 1995b; Gill-King 1997).

2.2.3.2 Organisms responsible for MFD

The desire to understand bone diagenesis has led to investigations into what kinds of organisms might be responsible, and what sort of conditions promotes or discourage their activity (Grupe & Piepenbrink 1989; Grupe *et al.* 1989; Balzer *et al.* 1997). The need to understand bone diagenesis was considered particularly pertinent to establishing what factors affect the likelihood of extracting viable biomolecules from archaeological bones. Different

microbiota exploit bone collagen in divergent ways and so it is important to distinguish what type of organisms are responsible for microscopic destruction (Grupe & Piepenbrink 1989; Grupe *et al.* 1989; Balzer *et al.* 1997). The size and shape of the MFD could correspond to a wide range of bacterial and fungal species (Hackett 1981). Few studies have observed remnants of microorganisms directly associated with penetrating tunnels in bone (Marchiafava *et al.* 1974; Hackett 1981).

2.2.3.2.1 Wedl MFD

Marchiafava *et al.* (1974) observed a direct association between colonisation of bone by fungus of the *Mucor* genus and microbial tunnelling of the kind that would be eventually classified as Wedl MFD. Marchiafava (1974) buried fresh human vertebrae obtained from dissection room cadavers in flowerpots full of moist topsoil and monitored which fungi developed. Microstructural tunnelling was observed when these specimens were examined using normal light microscopy and SEM. This tunnelling resembled Hackett's (1981) Wedl type. Three fungal species were found adhering to the vertebrae, but when a sample of rat bones was inoculated with each species separately, only the bone infected with *Mucor sp.* eventually demonstrated any tunnelling (Marchiafava *et al.* 1974).

Hackett (1981) attempted to replicate Marchiafava *et al.*'s results by inoculating fresh bone samples with fungus found adhering to buried archaeological human bone. This experiment failed to produce any characteristic tunnelling, although it was unclear whether the samples Hackett used included all of the microorganisms that were employed in the experiments of Marchiafava *et al.* (1974). Fernández-Jalvo *et al.* (2010) inoculated fresh sterilised animal bone with cultured fungal species of several genera. This experiment also confirmed that Wedl tunnels are caused by fungal organisms. The association between Wedl tunnelling and fungal organisms in bone recovered from terrestrial environments is now generally accepted (Hackett 1981; Child 1995b; Hedges 2002; Jans 2008).

Turner-Walker (2012) has questioned Marchiafava *et al.*'s (1974) conclusions. Some of the bones that Marchiafava *et al.* (1974) used had been autoclaved. This process would have cleaved the bonds between some of the bone proteins, making them easier for microorganisms to exploit. It was unclear from Marchiafava *et al.*'s (1974) study whether fresh or autoclaved bone was used for the successful production of Wedl MFD. If autoclaved bone had been used, then the samples would not have provided a realistic test of whether *Mucor*

sp. fungi are responsible for the occurrence of Wedl MFD in archaeological remains (Turner-Walker 2012). However, Turner-Walker does not address the results of the more recent experiments by Fernández-Jalvo *et al.* (2010), which supported Marchiafava *et al.*'s (1974) findings. It is probable that only certain species of fungi acting in certain environmental conditions are capable of producing Wedl tunnelling. Piepenbrink's (1986; 1989) failed inoculation experiments led them to surmise that some fungal species invade the bone substrate but do not produce characteristic tunnelling.

Wedl tunnelling associated with fungal exploitation of bone does not show any evidence for mineral redistribution as seen in the hypermineralised cuffs that surround non-Wedl MFD (Hackett 1981). The solubilised crystallites are not mobilised by this form of tunnelling, which suggests that either they are not readily incorporated into the organism's body or that absorption of the phosphate immobilises or kills the fungus (Marchiafava *et al.* 1974). However, other researchers have argued that the absence of mineral redistribution associated with fungal tunnelling implies that the phosphate is fully metabolised and transformed into substances that are not reprecipitated with the death of the organism (Hackett 1981; Piepenbrink 1986; 1989; Bolan 1991).

2.2.3.2.2 Non-Wedl MFD

The proliferators of non-Wedl MFD in bone have proven more difficult to isolate. Grupe *et al.* (1989) and Grupe & Dreses-Werringloer (1993) inoculated a sample of pig bones that had been sterilised using a 25 kGy dose of uranium radiation with a wide variety of fungal and bacterial species extracted from soils adjacent to a sample of bioeroded buried bone. The bacterial and fungal specimens were chosen on the basis of their ability to cleave bone proteins (Grupe & Dreses-Werringloer 1993: 31). Thin section microscopic examination combined with gram staining confirmed that each bone sample had been extensively colonised by bacteria and fungi (Grupe & Dreses-Werringloer 1993: 31). However, whilst the bacteria produced various pigmentations within the bone internal microstructure, they did not produce characteristic MFD (Grupe & Dreses-Werringloer 1993). Grupe & Dreses-Werringloer (1993) believed this negative result was due to the short incubation time and concluded that although fungi and bacteria can infect a bone very rapidly, associated destructive foci only begin to form at a late stage.

Child *et al.* (1993) attempted to identify the collagenase-producing microorganisms that would be capable of cleaving and exploiting bone proteins. They cultivated bacterial and fungal populations from soil, human skin and human faeces under aerobic and anaerobic conditions. Seventeen bacterial species tested positive for the production of collagenase at 10°C (average burial temperature in temperate conditions) (Child *et al.* 1993: 165). All of the collagenase-producing bacteria belonged to the *Clostridium* genus. Low numbers of these collagenase-producing bacteria are present within burial soils in northern Europe (Child 1995a; 1995b).

Balzer *et al.* (1997) inoculated a sample of pine marten bones with several different species of soil bacteria and left them to incubate for between eight and eighteen months. The bones were then thin sectioned, stained and examined using light microscopy to identify potential colonies. Bacteria had extensively colonised the bone samples, but had not produced characteristic MFD (Balzer *et al.* 1997: 420). The researchers extracted amino acids from each bone and compared them against quantities found within a fresh control. The infected samples retained depleted levels of proline and glutamic acid (Balzer et al 1997: 421). These substances are used by bacteria in the maintenance and growth of their cell walls (Balzer *et al.* 1997). The selective degradation of these amino acids could not be attributed to chemical diagenetic factors and must have occurred as a result of protein exploitation by invasive bacteria (Balzer *et al.* 1997). The authors suggested that, given longer incubation periods, this collagen exploitation would eventually lead to production of MFD (Balzer *et al.* 1997: 422). These findings suggested that microbial decomposition of bone is predominantly caused by bacterial organisms (Grupe & Turban-Just 1998). Hackett (1981) argued that non-Wedl MFD are too large (>2 microns) to have been made by single bacterium and are more likely to have been produced by larger demineralising fungal hyphae. However, this observation was made before SEM and measures of microporosity had established that non-Wedl MFD were composed of smaller honeycombed tubules (Yoshino *et al.* 1991; Jackes *et al.* 2001; Turner-Walker & Syversen 2002).

Dixon *et al.* (2008) cut samples from a single 700-year-old archaeological human bone specimen from Lincoln. These specimens were selectively inoculated with anaerobic *Prevotella intermedia* bacteria and left to incubate for 33 to 36 weeks. All samples demonstrated non-Wedl MFD to some degree, suggesting that microorganisms had exploited the bone before the samples had been taken. However, the samples that were treated with bacteria demonstrated higher concentrations of non-Wedl MFD than the non-infected samples, which suggested that non-Wedl MFD do occur as a result of the action of bacteria. These results should be treated with caution, as it was possible that they had captured natural variation in bioerosion within

the single skeletal element. It is generally accepted by most researchers that non-Wedl MFD are produced by species of bacteria (Jackes *et al.* 2001; Turner-Walker & Syversen 2002; Turner-Walker 2008; Turner-Walker & Jans 2008; Fernández-Jalvo *et al.* 2010; Turner-Walker 2012).

2.2.3.3 Bioerosion in Non-Terrestrial Environments

Ascenzi & Silvestrini (1984) identified specific types of bone bioerosion associated with submersion in sea water. They examined sections of bone from three incomplete skeletons recovered from two medieval shipwrecks that lay off of the coast of France. Ascenzi & Silvestrini also defleshed and sterilised fresh samples of cow bone and deposited them on the sea bottom. 'Boring' microtunnels matching the description of Hackett's Wedl-type were discovered in both the experimental cow and archaeological human samples (Ascenzi & Silvestrini 1984: 532). A large variety of micro-organisms were detected within the bored tunnels, including species of bacteria, algae and protozoans (Ascenzi & Silvestrini 1984: 535). The organisms responsible for bioerosion could not be discerned.

Bell *et al.* (1996) and Bell & Elkerton (2008) built upon Ascenzi & Silvestrini's (1984) findings in their analysis of forensic and archaeological human remains that had been deposited in marine, lacustrine and fluvial deposits. Bones that decomposed whilst immersed in sea water demonstrated initial peripheral Wedl tunnelling, similar to that described by Ascenzi & Silvestrini (1984) (Bell *et al.* 1996). A histomorphological study of human remains recovered from the Mary Rose shipwreck found off the coast of the Isle of Wight revealed patterns of peripheral Wedl tunnelling in bones that had not been covered by sediment in the initial period after deposition (Bell & Elkerton 2008) (Image 2.18). The Wedl-type bioerosion was restricted to sunlight-exposed bone surfaces, which indicated that endolithic cyanobacteria (blue-green algae) were likely to be responsible for biodeterioration (Bell & Elkerton 2008: 533). Turner-Walker & Jans (2008) observed similar peripheral tunnelling in faunal remains that had been collected from a gravel beach at an undisclosed location in Cyprus and a freshwater riverbed in West Runton, Norfolk. The microbial attack observed within the Cypriot and West Runton specimens resembled the tunnelling bioerosion produced by endolithic filamentous cyanobacteria in marine shells (Turner-Walker 1999; Turner-Walker & Jans 2008: 233).

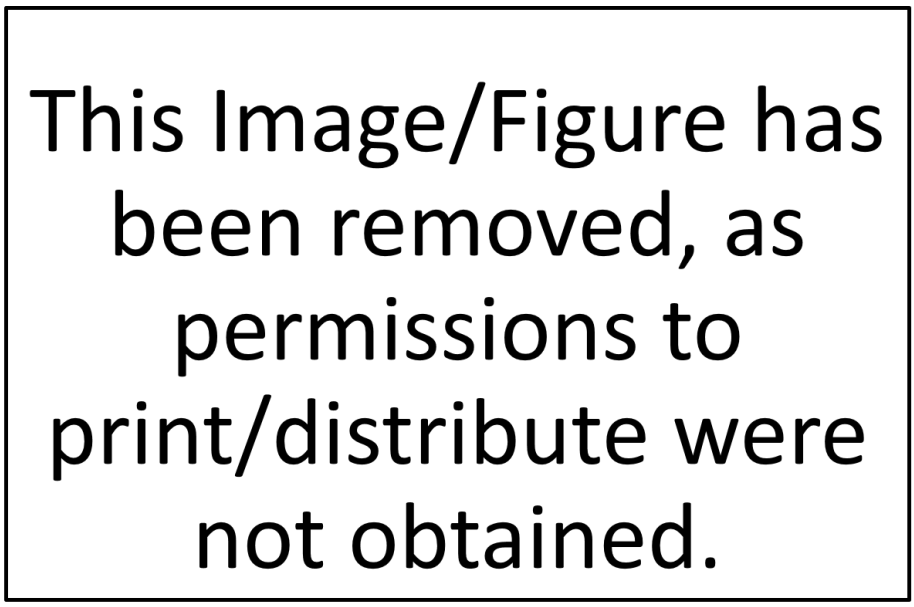

Image 2.18: BSEM of the alveolar margin of a mandible associated with the Mary Rose shipwreck. Wedl tunnelling can be observed at the peripheries (Bell & Elkerton 2008: 531).

Pesquero *et al.* (2010) identified a form of bone bioerosion that was specifically related to aquatic and lacustrine burial contexts. Optical microscopy and SEM analysis of bones sampled from Miocene mammals excavated from a lake deposit revealed peripheral Wedl tunnelling that included hypermineralised zones similar to those observed in non-Wedl MFD (Pesquero *et al.* 2010). Mineralised microspheres were observed within the destructive tunnels. Pesquero *et al.* (2010: 197) interpreted these structures as fossilised bacteria. Pesquero *et al.* (2010) did not give a specific name to this type of attack nor the likely organisms responsible, although it was probably that they were specific to the lacustrine environment.

2.2.3.4 An Endogenous Model

The identity and derivation of the bacteria that produce non-Wedl MFD is still under question (Child 1995a; 1995b; Bell *et al.* 1996; Jans *et al.* 2004, Jans 2008, Turner-Walker 2008; Turner-Walker 2012). The limited success of investigations into the instigators of non-Wedl MFD may be a result of the assumption that the majority of the degradation takes place after skeletonisation and is driven by soil bacteria. This concept embodies a strict definition of diagenesis, as it presumes all processes occur as a result of the physical and chemical interactions with the burial environment. It is likely that at least some, if not, all bacterial bone

bioerosion could be caused by microorganisms that were intrinsic to an organism at the point of death (Janaway 1987; Child 1995a; 1995b; Bell *et al.* 1996; Jans *et al.* 2004).

Putrefaction is often used interchangeably with terms referring to overall bodily decomposition. A strict definition of putrefaction refers specifically to the initial phase of decomposition that is mediated by intrinsic chemical and biological processes (Polson *et al.* 1985; Clark *et al.* 1997). The first stage of bodily decomposition is cell autolysis, which begins immediately after death (Janssen 1984; Polson *et al.* 1985; Janaway 1987; Gill-King 1999; Dent *et al.* 2004). The cells of a body are able to exploit the energy within the covalent bonds of carbohydrates through the production of enzymes, within narrow environmental conditions and the presence of oxygen (Gill-King 1999). When the heart stops beating, the body's cells no longer receive the nutrients and oxygen they require to maintain their structural integrity through biosynthesis and subsequently they begin to collapse (Janssen 1984; Gill-King 1999). Cell death releases organic acids and protease enzymes from the lysosomes into the surrounding environment which accelerate chemical degradation of the soft tissues (Janssen 1984; Clark *et al.* 1997). This process represents the sterile autolysis phase of decomposition (Janssen 1984; Clark *et al.* 1997; Gill-King 1999).

Mammalian gastrointestinal tracts contain abundant species of bacteria which are responsible for a variety of beneficial processes in life (Hao & Lee 2004; Ley *et al.* 2008). Autolysis leads to the breakdown of a body's mucosal membranes that confine intrinsic bacteria to their specific functional locales (Child 1995a; 1995b; Gill-King 1999). Intrinsic bacteria are free to transmigrate around the body and exploit the soft tissues once the immune system fails and the mucosal membranes have collapsed (Jansen 1984; Child 1995a; 1995b; Gill-King 1999). Aerobic bacteria transmigrate from the viscera initially (Polson *et al.* 1985; Janaway 1996; Child 1995a). However, the release of organic acids promoted by autolytic destruction and bacterial respiration rapidly changes the decompositional environment from aerobic to anaerobic and acidic (Polson *et al.* 1985; Child 1995a; 1995b; Gill-King 1999). Most human enteric intestinal bacteria are anaerobic and thrive within these new conditions (Polson *et al.* 1985; Gill-King 1997; Child 1995a). Anaerobic visceral bacteria are mostly responsible for putrefactive soft tissue loss (Polson *et al.* 1985; Child 1995a; Bell *et al.* 1996).

Bacteriological studies of *post mortem* blood have found that visceral bacteria transmigrate into a body's vasculature within twenty-four hours after death (Martinez *et al.* 1985; Polson *et al.* 1985; Child 1995b; Bell *et al.* 1996; Tuomisto *et al.* 2013). These bacteria can enter the bone via the blood vessels that lie inside the Haversian canals (Child 1995a; Child 1995b; Bell *et al.*

1996). Visceral bacteria are specifically adapted to breaking down bodily proteins, including collagen (Child 1995a; Gill-King 1999). Autolytic and putrefactive changes are capable of promoting complete skeletonisation of a corpse (Clark *et al.* 1997). Therefore, in the early *post mortem* period the bones of a decomposing cadaver are surrounded by a volatile environment that includes high numbers of putrefactive bacteria specifically adapted to breaking down bodily proteins. It seems likely that the microorganisms associated with this phase of bodily decomposition have the opportunity and the means to engender high levels of diagenetic alteration to the internal bone microstructure before a corpse has skeletonised (Child 1995a; 1995b; Bell *et al.* 1996; Janaway 1996). Aerobic bacteria present within the external environment degrade the superficial soft tissues of a cadaver and will eventually spread internally once the environment of the decomposing body becomes oxygenated (Janssen 1984; Janaway 1996; Gill-King 1997). This later stage of bacterial action is referred to as decay (Fielder & Graw 2003; Kakizaki *et al.* 2011).

The mechanisms of endogenous bone bioerosion are similar to those outlined previously and are probably comparable to those that cause carious lesions in teeth (Child 1995a; Bell *et al.* 1996). Bacterial exploitation of organic structures rarely involves a single species of bacteria (Pitre *et al.* 2013). A bacterial biomass containing several different species usually works together in breaking down particular organic materials (Pitre *et al.* 2013). *Clostridia sp.* bacteria, particularly *Clostridium histolyticum* represent the genus and species most capable of exploiting collagen within a hydroxyapatite matrix (Child 1995a; 1995b; Bell *et al.* 1996; Janaway 1996). This genus is found within most soils, but predominates amongst mammalian visceral bacteria and is known to play an active role in soft tissue decomposition (Child 1995a; Bell *et al.* 1996; Grupe 2001; Jackes *et al.* 2001; Janaway 2001). Jackes *et al.* (2001) used SEM to examine the shape of the tubules that constitute the spongiform structure of non-Wedl MFD. The morphologies of the cavities were consistent with bodies of *Clostridium sp*. including *Clostridium histolyticum* (Jackes *et al.* 2001: 420).

Clostridium sp. is known to excrete effective collagenase and has consistently been isolated as a prospective instigator of non-MFD (Mandl *et al.* 1958; Child 1995a; Grupe 2001; Jackes *et al.* 2001; Grupe & Dreses-Werringloer 1993). However, there is some debate as to whether this genus could be responsible for bacterial degradation of buried archaeological bone, due to its narrow temperature range tolerance (Child 1995b). *Clostridium* species have been observed to produce collagenase at the low temperatures found in burial contexts (Child *et al.* 1993; Child 1995a). The exothermic autolytic chemical reactions that occur during cell death maintain

elevated temperatures within a putrefying body (Mant 1987; Janaway 1987; Janaway 1996; Clark *et al.* 1997).

Jackes *et al.* (2001) inoculated fresh human bone samples with *Clostridium sp.* bacteria in an attempt to reproduce non-Wedl MFD. One species was observed to attack and demineralise the bone but did not produce characteristic MFD. It may be significant that *Clostridium histolyticum* could not be used in this study as it was classed as a biohazard (Jackes *et al.* 2001: 428). Child's (1995) observation that only a small percentage of bacteria from most burial soils are able to break down collagen at the low temperatures of a burial environment suggests that a decomposing organism's gut represents the most abundant repository of collagenase-producing bacteria within most burial environments. It is reasonable to suggest that endogenous bacteria might be responsible for some, if not the majority, of internal bacterial bone bioerosion found within archaeological remains.

2.2.3.5 Endogenous versus Exogenous

It is important to establish whether bone is predominantly degraded by endogenous rather than exogenous microorganisms as either scenario has different implications for mechanisms of microscopic bone degradation. In either case these processes can be related directly to survival of bone in the ground and the potential for extracting biomolecules (Grupe *et al.* 1989; Balzer *et al.* 1997; Jans *et al.* 2002; Reiche *et al.* 2003). An endogenous model of bioerosion would suggest that the survival of organic molecules in bone will be dependent on the conditions of early decomposition. The suggestion that bacterial bioerosion is controlled by interaction with endogenous bacteria underpins all attempts to reconstruct early taphonomic events, such as mortuary processes (Hollund *et al.* 2012). An exogenous model of bioerosion suggests that bimolecular yield would be dependent on the conditions of the burial environment and how they changed over time in ways that promoted or discouraged the activity of soil microorganisms.

Child (1995) suggested that endogenous bacteria would not have chance to exploit the bone to any great extent before they were out-competed by aerobic soil bacteria. The anaerobic endogenous microbiota might aid in the initial 'foothold' demineralization of the inorganic phase required for later aerobic organisms to access the bone protein (Child 1995a; 1995b; Hedges 2002). Janaway (1987) suggested that exogenous bacteria from densely packed

cemeteries will be more competitive, as the generations of bacterial colonies will have adapted to degrading human bone.

It has proven difficult to recreate *in vitro* the immediate *post mortem* conditions of a putrefying body as opposed to a fresh bone in contact with the soil. The conditions of bodily putrefaction are difficult to measure without upsetting the environment and potentially influencing the result (Mann *et al.* 1990; Janaway 1996; Campobasso *et al.* 2001; Adlam & Simmons 2007; De Jong *et al.* 2007). Some species of visceral bacteria are known, but their exact ratios and abundance, as well as the specific pathways of their transmigration, have yet to be established (Gill-King 1997). Some of the bacteria that are likely to play a significant role in bone bioerosion are common to both mammalian viscera and most soils. Confirmation of the species of bacteria responsible for non-Wedl MFD, would not significantly increase clarity regarding the endogenous versus exogenous question (Child 1995a; Grupe 2001).

2.2.3.5.1 Experimental & Forensic Studies

Most of the arguments for an endogenous or exogenous origin for osteolytic bacteria have focussed on identifying which model best fits the trends in bacterial tunnelling observed amongst archaeological and forensic bones (Yoshino *et al.* 1991; Bell *et al.* 1996; Hedges *et al.* 1995; Nielsen-Marsh & Hedges 2000; Jans *et al.* 2004; Nielsen-Marsh *et al.* 2007; Turner-Walker & Jans 2008) (Table 2.1). Yoshino *et al.* (1991) examined the histology of humeral samples taken from human bodies that had been experimentally buried, exposed or submerged in sea water for up to fifteen years. They periodically removed samples from humeri for SEM analysis to monitor the point at which the bone microstructure began to be degraded by bacteria. They found non-Wedl MFD in the periosteal compact bone of one set of buried remains after 2.5 years of deposition (Yoshino *et al.* 1991: 146). Most inhumed samples were not attacked until five years after burial. Particles of bacteria and fungi were found within the MFD but also within undamaged aspects of the bone. The surface-deposited remains did not show any signs of bioerosion until fifteen years after deposition (Yoshino *et al.* 1992). Yoshino *et al.* (1991: 151) argued that their results suggested that bacterial diagenesis coincided with skeletonisation and exposure of the bone to soil microbiota. The early detection of MFD in a humeral sample that had been buried for 2.5 years was argued to have occurred as the result of shallow burial which could have promoted rapid skeletonisation (Yoshino *et al.* 1991: 152).

Endogenous	Exogenous
MFD appear early *post mortem.*	MFD appear late *post mortem.*
MFD appear before skeletonisation.	MFD appear after skeletonisation.
The extent of bone bioerosion correlates with evidence for early taphonomic events that would have affected endogenous microbial access.	The extent of bone bioerosion correlates with features of the site environment that would have affected exogenous microbial abundance.
MFD are focussed around vascular structures and are controlled by the internal architecture.	MFD are independent of the bone microstructures.
Bones from bodies that had decomposed on the ground surface will demonstrate minor bioerosion that is distributed throughout the sample.	Bones from bodies that had decomposed on the ground surface will show minor bioerosion at points where they were in contact with the soil.
Bone from a body that was disarticulated soon after death will demonstrate limited levels of bioerosion compared with bone from an organism that decomposed in articulation.	There will be no significant difference between levels of bacterial bioerosion in articulated and disarticulated remains.
Bone from a mummified individual may demonstrate minimal bacterial attack.	Bone from a mummified individual will always demonstrate no bacterial attack.
Bones that are located closer to the gut will be more severely affected by bacterial attack.	Porous bones will be more severely affected by bacterial attack.
Bioerosion will be present to a certain extent within bones recovered from sterile burial environments.	Bioerosion will be absent within bones recovered from sterile burial condition.
Neonates will be more likely to show no evidence for bacterial alteration.	Neonates will be equally affected as adults by bacterial alteration.
Bioerosion will not vary with the age-at-death of an individual.	Bioerosion will be more extensive within bones from older individuals.

Table 2.1: A set of predictions and observations adapted from histomorphological studies of archaeological and forensic bone that have been used to assess whether MFD are caused by endogenous or exogenous bacteria.

The results of Yoshino *et al.* (1991) were contradicted by Bell *et al.* (1996), who performed similar analyses on the reclaimed remains of missing persons where the *post mortem* interval was known. Non-Wedl MFD were detected in several of the bone samples. The earliest recorded appearance of non-Wedl MFD was three months *post mortem* (Bell *et al.* 1996: 132). This specimen originated from a set of human remains that had been scavenged by a carnivore and left on the ground surface to decompose (Bell *et al.* 1996). Non-Wedl MFD had formed around Haversian canals and at the sites of enlarged osteocyte lacunae (Bell *et al.* 1996). The thin section of a rib recovered fifteen months *post mortem* from the surface of a muskeg bog demonstrated extensive bacterial alteration (Bell *et al.* 1996: 132). However, a sample of rib

fragment from a body that had been inhumed for seventy years, albeit coffined six feet beneath the ground and covered in slaked lime, demonstrated only minor signs of bacterial damage (Bell *et al.* 1996: 132). Six specimens of bone whose *post mortem* period ranged from one to eighty-three years were entirely unaffected by bioerosion (Bell *et al.* 1996: 136).

Bell *et al.*'s (1996) study demonstrated that bacterial MFD can form in the early *post mortem* period (Bell *et al.* 1996). It is difficult to say whether these findings support an endogenous or exogenous origin for the osteolytic bacteria, as all of the samples had skeletonised before they were retrieved. Bell *et al.* (1996: 138) suggested that the early appearance of MFD three and eighteen months after death strongly indicated that endogenous bacteria were involved in initial bioerosion of bone. Both sets of remains in Bell *et al.*'s (1996) study demonstrated MFD had been exposed on the ground surface. Yoshino *et al.*'s (1991) findings suggested that these bones should not have been available for exploitation by soil microbes. The limited bioerosion observed in the bones of the scavenged individual could be explained by the biostratinomic action of fauna. The scavenging fauna would have swiftly skeletonised the corpse and removed the internal organs along with any associated deleterious bacteria before the microorganisms had chance to access the bone (Bell *et al.* 1996: 137).

Yoshino *et al.* (1991) said little about the treatment and position of the remains that they examined. They did not directly refer to the rate of skeletonisation in their experimental remains and relied upon observations relayed in separate reports. The early occurrence of non-Wedl MFD in one of their samples was explained by this specimen having been buried shallowly, but this justification was speculative (Yoshino *et al.* 1991: 152). The researchers may not have directly handled or perceived the whole bodies *in situ*, and so the state of each body's decomposition was an unknown quantity. It was debateable whether the beginnings of bacterial attack in the bone examined in Yoshino *et al.*'s (1991) study could be related directly to the point at which soft tissue was lost, as there was no discussion of the speed of bodily decomposition in each case.

It is difficult to account for the lack of bioerosion observed in the majority of Bell *et al.*'s (1996) skeletonised samples from an endogenous model of decay, as it was clear that they had all undergone putrefaction. It may be significant that the bone samples that were unaltered by bacteria originated from the skeletons of 20th century executed prisoners that had been buried deep underground and treated with slaked lime (Bell *et al.* 1996: 136). The cold and hypoxic conditions facilitated by deep burial can interfere with natural bodily decomposition, as can the application of slaked lime (Schotsmans *et al.* 2012).

2.2.3.5.2 Archaeological Studies

The failed attempts to discern the aetiology of non-Wedl MFD by documenting its development in real-time experiments or inoculations led to a shift in methodology. Researchers began to focus on the archaeological material, where bacterial attack had run its full course. The factors that could be discerned to have influenced the development of non-Wedl MFD across numerous sites were used to implicate whether endogenous or exogenous bacteria were likely to have been responsible.

A histomorphological study of 119 human bones excavated from a group of Middle to Late Woodland period Native American burial mounds from the Lower Illinois Valley found that the variation in histological integrity was not related to site environment (Hanson & Buikstra 1987). Twenty-five per cent of the samples were entirely destroyed by bacterial tunnelling, and the rest demonstrated variable levels of attack. The researchers made no mention of the state of the remains at recovery and so this study could not be used to discern the relationship between early taphonomy and bone bioerosion.

Nielsen-Marsh & Hedges (2000) examined several diagenetic parameters of 134 bones of several species from eight archaeological sites. They concluded that diagenetic degradation of bones was dependant on hydrological features of the environment. The diagenetic parameters of bone recovered from waterlogged or dry environments indicated that these specimens were well-preserved. Bone excavated from contexts that were periodically recharged by flood or rainwater tended to have been severely altered by bacterial and chemical erosion (Nielsen-Marsh & Hedges 2000: 1146). Bone bioerosion was related to site hydrology to some extent, but not to in the same way as other measures of bone diagenesis (Nielsen-Marsh & Hedges 2000: 1143). An unknown factor had affected microbiological decomposition of bone at the sites where there was no association with hydrology.

The extent to which bacterial diagenesis might be affected by hydrology of a site environment was also investigated by Reiche *et al.* (2003). They studied diagenetic parameters of bone from the Neolithic site of Bercy in northern France. Some bone specimens had been deposited within permanently waterlogged contexts whereas others would have been subjected to variable wetting and drying cycles. Bones from waterlogged environments demonstrated better histological preservation than bones from environments with more inconsistent hydrological regimes.

It is difficult to gauge the extent to which the relationships between histological bone preservation and site environment support an endogenous or exogenous origin for bacterial destruction of bone. The correlations between histological integrity and environmental changes would superficially suggest that exogenous bacteria are responsible for non-Wedl MFD, as those organisms are more likely to be affected by specific environmental changes (Nielsen-Marsh & Hedges 2000; Reiche *et al.* 2003). The anoxic conditions promoted by waterlogging would inhibit the activity of osteolytic soil bacteria and promote high levels of histological bone preservation (Bottrell *et al.* 1998; Turner-Walker & Jans 2008; Turner-Walker 2012). However, waterlogged burial conditions would also favour good histological bone preservation under an endogenous model of bioerosion. Water saturation and accompanying anoxia prevents or subdues soft tissue decomposition and interferes with the spread of deleterious endogenous microorganisms (Polson *et al.* 1985; Mant 1987; Janaway 1996; Turner & Wiltshire 1999; Fiedler & Graw 2003; Turner-Walker & Jans 2008; Hollund *et al.* 2012; Ubelaker & Zarenko 2011).

Jans *et al.* (2004) studied 250 faunal and human bones from 41 archaeological sites using microscopy and HgIP. The faunal assemblages consisted of articulated skeletons as well as butchered disarticulated remains of domesticated animals. The human bones from across all sites originated from articulated skeletons recovered within discrete burials. Bacterial MFD in all specimens converged around Haversian canals in osteonal systems, particularly at the site of osteocyte lacunae (Jans *et al.* 2004: 91). Bacteria had not invaded directly through the periosteum, but relied upon an organism's vasculature (Jans *et al.* 2004: 91). Bones from near the abdominal area (ribs, vertebrae) were more grossly affected by bacterial bioerosion (Jans *et al.* 2004: 91). Jans *et al.* (2004) found that the articulated human bone was significantly more likely to have been extensively attacked by non-Wedl MFD than the bone from the disarticulated fauna. The disarticulated butchered faunal bones demonstrated higher occurrences of fungal tunnelling (Jans *et al.* 2004: 91). The only faunal material that showed evidence for extensive bacterial bioerosion was that which originated from articulated non-butchered skeletons (Jans *et al.* 2004: 91).

The most obvious difference between the human and faunal assemblages was taphonomic histories, specifically the evidence for butchery, which also dictated the occurrence of bacterial bioerosion within the faunal remains when they were examined in isolation (Jans *et al.* 2004). Most of the domesticate bones had been butchered and separated from their viscera in the early *post mortem* period whereas the human bodies had been buried articulated with their organs intact (Jans *et al.* 2004: 91). The low levels of non-Wedl MFD within the butchered

assemblage was attributed to the separation of the bones from the source of deleterious bacteria in the early *post mortem* period. The relatively high incidence of fungal tunnelling in the butchered animal bone was explained by the opportunistic action of exogenous saprophytic fungi that could freely access nutrient rich organic bone post-skeletonisation. This evidence was used to argue that bacteria responsible for the non-Wedl-MFD must have been endogenous to the organism and associated with putrefaction (Jans *et al.* 2004: 92).

The results of Jans *et al.* 2004 were reinforced by Smith *et al.* (2007) and Nielsen-Marsh *et al.* (2007) who also studied bone diagenesis amongst large numbers of bone samples from varied sites and environments. Smith *et al.* (2007) found that microbial degradation was the most common form of diagenetic degradation in bone from chemically benign environments. This finding supported similar observations by Turner-Walker *et al.* (2002). Nielsen-Marsh *et al.* (2007) used HgIP and thin section microscopy to examine 219 archaeological bones of variable species from a variety of European Holocene sites. Specific chemical tests were performed on the burial soils that provided parameters of organic content, pH, exchangeable acidity, conductivity and the presence of water soluble cations and anions. These features would have affected the abundance and character of soil bacteria. These parameters were used to define particular soil types that could be used to gauge environmental influences on the various diagenetic pathways.

Nielsen-Marsh *et al.* (2007) found that only catastrophic dissolution correlated with burial conditions and that bacterial attack was the sole form of degradation found in bone from benign contexts (Nielsen-Marsh *et al.* 2007: 1529). There was no correlation between bacterial bioerosion and soil characteristics. Articulated human bone was more likely to have been affected by bacterial MFD than disarticulated, butchered bone from domesticated animals. These findings reinforced the conclusions of Jans *et al.* (2004) regarding the relationship between taphonomy, putrefaction and bacterial attack to the internal bone microstructure, as well as the lack of an association between bacterial bioerosion and environmental conditions.

Turner-Walker (2008) has questioned the conclusions of both Jans *et al.* (2004) and Nielsen-Marsh *et al.* (2007) and suggested that an exogenous model of bacterial bioerosion would be equally as applicable. The discrepancy in bacterial bioerosion between articulated human and disarticulated animal bone was more likely to have occurred as a result of the restricted age-at-death range of the butchered carcasses (Turner-Walker 2008). In the interests of maintaining the highest quality of meat with the smallest invest of resources, most domesticated animals reared for consumption are usually slaughtered during or just after

adolescence (Turner-Walker 2008). The low level of Haversian bone within the young, butchered bone would have meant that these remains were less porous and less susceptible to invasion by soil bacteria than the human remains, which would have presumably originated from individuals of variable age (Turner-Walker 2008).

Histomorphological investigation of bone samples taken from some of the individuals buried and killed in Roman Pompeii, Campania by the eruption of Mount Vesuvius in A.D. 79 also provided evidence that bacterial MFD are produced by endogenous microbes. Cipollaro *et al.* (1998) and Guarino *et al.* (2006) studied the microstructure of bone removed from buried Roman skeletons from Pompeii using thin section light microscopy and SEM. They discovered that most bones were free from bacterial bioerosion, but a minority had been extensively altered by non-Wedl MFD (Cipollaro *et al.* 1998: 902; Guarino *et al.* 2006: 517). All of these skeletons had been buried beneath hot volcanic pyroclastic material that would have remained sterile over the period of burial. The extensive bacterial attack observed in the Pompeian bone sections could only have been driven by internal microbiota (Guarino *et al.* 2006: 518). Guarino *et al.* (2006) could not explain why only a small proportion of bones were affected by bacterial attack, as presumably all of the individuals were buried with their organs intact.

A common observation amongst histological studies of archaeological bone is that the periosteal and endosteal fringes of a bone sample often remain intact whilst the rest of the section has succumbed to the highest levels of bacterial tunnelling (Hanson & Buikstra 1987; Bell *et al.* 1996; Jans *et al.* 2004; Parker Pearson *et al.* 2005; Hollund *et al.* 2012). Hollund *et al.* (2012) argued that the ubiquity of this phenomenon was consistent with bacterial attack originating from inside of the body, as there was no reason why osteolytic soil bacteria could not tunnel directly through the periosteal and endosteal surfaces post-skeletonisation. However, Child (1995a; 1995b) and Turner-Walker (2012) suggested that it is more convenient for soil bacteria to access the bone microstructure via the natural microscopic channels. Hedges (2002) suggested that the periosteal bone surface is more likely to have been infiltrated by substances from the external environment, such as humic acids, which would have discouraged microbial bioerosion through the deactivation of protease and cross-linking of organic molecules. However, both the exogenous bacteria and humic factors within the soil would have been able to infiltrate the bone at a similar point after skeletonisation and so the argument of osteolytic inhibition by humic cross-linking is not entirely cogent.

The study by Dixon *et al.* (2008) that involved the inoculation of a single archaeological bone sample with a particular species of bacteria is interesting in this scenario, as the bacterial species that was used, *Prevotella intermedia*, is an obligate anaerobe. Dixon *et al.* (2008) concluded that the relative success of their experiment compared with similar inoculations of bone with aerobic soil bacteria, suggested that anaerobic bacterial species were responsible for non-Wedl MFD. Anaerobic bacteria constitute the majority of the gut microbiota that are associated with putrefaction, and so Dixon *et al.*'s (2008) results suggested that the organism's gut represents the most likely origin of osteolytic bacteria (Janaway 1996; Gill-King 1999).

Trueman & Martill (2002) examined the histology of 350 fossil bones spanning more than 350 million years. They found that these bones were characterised by a lack of evidence for internal microbial decomposition. It was evident that soil bacteria had failed to colonise and exploit these bone samples over their long periods of decomposition. This notion led Trueman & Martill to conclude that bacterial degradation must occur in the early *post mortem* period and that an early taphonomic event prevented bacterial bioerosion in each case (Trueman & Martill 2002).

2.2.3.5.3 Recent Experiments

More recent studies have provided evidence that soil bacteria might still exert an influence on the occurrence of MFD. Fernández-Jalvo *et al.* (2010) examined the histological structure and protein content of bones from ten sheep carcasses that had been exposed on an upland environment for up to 30 years in Neuadd, Central Wales, U.K. The majority of these bones were histologically well-preserved after 30 years. Non-Wedl MFD were observed in a low proportion of bone samples. Most of this attack was limited to the sub-periosteal and sub-endosteal zones and was only observed to consume the majority of the histological structure in two bone samples; a vertebra that had been placed in a manure heap post-skeletonisation and a femur that had lain exposed on a peat bog for twelve years.

Fernández-Jalvo *et al.* (2010: 76) suggested that the organisation and interaction of non-Wedl MFD amongst their samples was consistent with separate phases of microbial invasion. These phases of attack suggested that bones had been subjected to numerous distinct waves of bacterial invasion (Figure 2.5). A mandible from a sheep that had been defleshed and buried in a manure pit did not demonstrate any evidence phased invasion of bacterial colonies. Fernández-Jalvo *et al.* (2010: 76) argued that the lack of evidence for phasing suggested that

the microbial bioerosion had occurred as one distinct incursion. The phased patterns of bacterial bioerosion within the sheep bone from the stream were ascribed to seasonal variation in environments having differentially affected the action of soil bacteria. This argument presumed that endogenous bacterial attack is a singular process and would not produce temporally distinct waves of invasion.

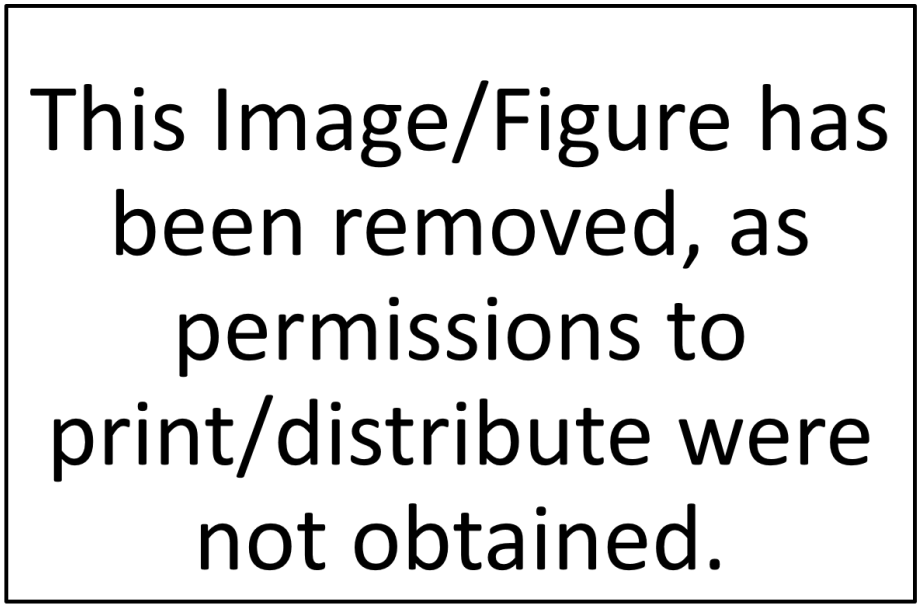

Figure 2.5: BSEM image of a transverse section of sheep mandible that was experimentally deposited within a riverbed in Neuadd, Wales showing phased bacterial tunnelling. The areas marked in black represent the secondary wave of bacterial attack, earliest to latest (a-c) (Fernandez-Jalvo et al. 2010: 76).

Fernández-Jalvo *et al.* (2010: 70) noted that the focal destruction in the well-preserved samples from Neuadd did not correspond to vascular structures and was randomly dispersed. This result indicated that all non-Wedl MFD must be produced at a late stage by external soil bacteria (Fernández-Jalvo *et al.* 2010: 80). The season of death of each carcass did not correspond with the presence or extent of non-Wedl MFD. Season of death has consistently been recognised as the primary influence on the rate of bodily decomposition (Rodriguez & Bass 1983; 1985; Vass 2011). The lack of association between seasonality and bone bioerosion suggested that exogenous microorganisms drive bacterial bioerosion of bone (Fernández-Jalvo *et al.* 2010: 80).

Carnivore tooth marks found on one of the carcasses included in Fernández-Jalvo *et al.*'s (2010) study indicated that the specimen had been scavenged. The rest of the bodies had decomposed without any major faunal disturbance. Scavenging rapidly removes the soft tissue

that facilitates the growth of endogenous microbes. Under an endogenous model of decay, it would be predicted that bones from the scavenged sample should demonstrate low levels of bacterial attack (Bell *et al.* 1996; Jans *et al.* 2004; Fernández-Jalvo *et al.* 2010: 78). Fernández-Jalvo *et al.* (2010) found no significant differences in the histological alteration of scavenged and non-scavenged samples. The lack of association between non-Wedl MFD and vascular microstructural features supported a model of later bacterial attack originating from the soil.

The sheep specimen that was buried in a manure heap after being defleshed by exposure demonstrated extensive levels of bacterial attack. The majority of attacking bacteria must have come from the surrounding burial context as all of the other exposed bones in Fernández-Jalvo *et al.*'s (2010) sample were only affected by minor levels of bioerosion. However, the manure burial context of the sheep bones would have incubated an abundance of mammalian gut bacteria that could have mimicked endogenous bacterial attack. Fernández-Jalvo *et al.* (2010) did not explain the presence of bioerosion within surface-deposited remains that had not been in contact with the soil.

Turner-Walker (2012) cut samples from three butchered and defleshed cow metapodials and placed them in different positions next to a stream located on the campus of the National Yunlin University of Science and Technology in Central Taiwan. One sample was placed within the dry soil adjacent to the stream, another within the permanently waterlogged stream bank and the final one at the bottom of the stream bed. The dry and waterlogged samples were retrieved after one year and the riverbed specimen was retrieved after six months. Sections of the samples were analysed by Turner-Walker using BSE-SEM. The bone from the waterlogged deposit was heavily cracked and demineralised, but was free from all forms of bioerosion. The bone recovered from the riverbed demonstrated Wedl-type tunnelling of the type that has been associated with cyanobacteria (Bell & Elkerton 2008). The bone from the dry soil demonstrated minor alterations consistent with non-Wedl MFD. The identification of non-Wedl MFD within the dry soil sample, and its absence from the other material confirmed to Turner-Walker that bacteria bioerosion is mediated by aerobic soil microorganisms (Turner-Walker 2012).

It is difficult to say how far Turner-Walker's (2012) experimental study contributes to the interpretation of internal bioerosion within archaeological specimens from temperate Europe. The humidity and temperature associated with the tropical climate of Taiwan would provide the optimum environmental conditions for bacteria (Carter *et al.* 2007; 2010; Ross & Cunningham 2011). Turner-Walker (2012) does not mention whether the bacteria present

within Taiwanese soils were typical of those that occur within temperate Europe. Turner-Walker's results contrast with findings that dismembered and defleshed cow bones that had been deposited and exposed to soil bacteria at Overton Down, Wiltshire for thirty-two years, demonstrated no non-Wedl MFD (Nielsen-Marsh & Hedges 2000).

Turner-Walker (2012) makes no mention of whether the cow bones used in his experiment were sterilised before they were placed in their respective environments or whether any control samples were taken and tested. The same environments that discourage soil bacteria also prevent the activity of putrefactive visceral microbiota (Turner & Wiltshire 1999; Jans *et al.* 2004; Hollund *et al.* 2012). The speed of *post mortem* transmigration of gut microbiota suggests that Turner-Walker's bone samples may have been infected by gut microbiota before they were acquired (Polson *et al.* 1985; Bell *et al.* 1996; Gill-King 1997). Small amounts of putrefactive gut bacteria are sometimes recovered from within fresh meat (Gill *et al.* 1976; Gill 1979). Endogenous biodegradation of the bone by gut bacteria could have occurred whilst the bone was in the dry ground. The inhibitory effects of the other two depositional environments would have ensured that the additional samples remained free from putrefactive bacterial attack.

Turner-Walker (2008) and Turner-Walker & Jans (2008: 231) suggested that the immaculate histological preservation of medieval human bone excavated from Trondheim, Norway indicated that bacterial bioerosion could not be endogenous and linked with putrefaction. The soft tissue of the Trondheim bodies had decomposed, yet the bones had not been bioeroded (Turner-Walker 2008). The cold temperatures and hypoxia of the deep waterlogged burial environment would have produced a sterile burial environment (Turner-Walker 2008). Under an exogenous model of bone bioerosion, this detail would explain the high level of histological bone preservation (Turner-Walker & Jans 2008: 231). However, cold temperatures and anoxia would also have hindered the majority of the collagenase-producing putrefaction bacteria (Child 1995a). The organisms that produce protease are more abundant and versatile than those that produce collagenase (Polson *et al.* 1985; Child *et al.* 1993; Child 1995a' 1995b). Their survival at Trondheim was attested to by the loss of soft tissue (Child 1995a). Soft tissue can be lost entirely through sterile autolytic change and hydrolytic reactions with water (Polson *et al.* 1985; Carter *et al.* 1997).

2.2.3.5.4 A Real-time Experiment

White (2009) selectively buried and exposed pig carcasses for set amounts of time and examined their bone microstructures using thin section microscopy in order to determine the origin of osteolytic bacteria. A mixture of juvenile, neonatal and stillborn carcasses were buried in the soil, exposed on the ground surface or contained in plastic boxes in woodland near Riseholme, Lincolnshire, U.K. Pigs buried in boxes were either left uncovered, buried in soil from a nearby cemetery or buried in sterile sand. Decomposition of the pigs was monitored regularly over three years and their bones sampled for thin section light microscopy. Some of the early sections were stained using Methylene Blue and Gram staining to detect the presence of bacteria prior to them exploiting the bone collagen.

Gram-positive and Gram-negative bacteria were found to have extensively colonised bone samples within one month *post mortem* (White 2009: 176). No MFD were observed in these samples until six months *post mortem* (White 2009: 183). The non-Wedl MFD began as much smaller tunnels that resembled enlarged osteocyte lacunae (termed pre-tunnelling), which eventually coalesced to form the characteristic microfocal destruction (White 2009: 161). All of the mature remains demonstrated microbial tunnelling to some extent after one year, but the bones from the buried pigs were much more severely affected than those that had been exposed on the ground surface (Image 2.19). The carcasses that had been deposited on the ground surface had decomposed and skeletonised within six to fourteen weeks. The buried remains were still actively decomposing when they were sampled after one year. This disparity in rates of decomposition between buried and exposed remains has been linked with the increased abundance and variety of carnivorous insects that can access and skeletonise an unburied corpse (Rodriguez & Bass 1983; Bell *et al.* 1996; Simmons *et al.* 2010).

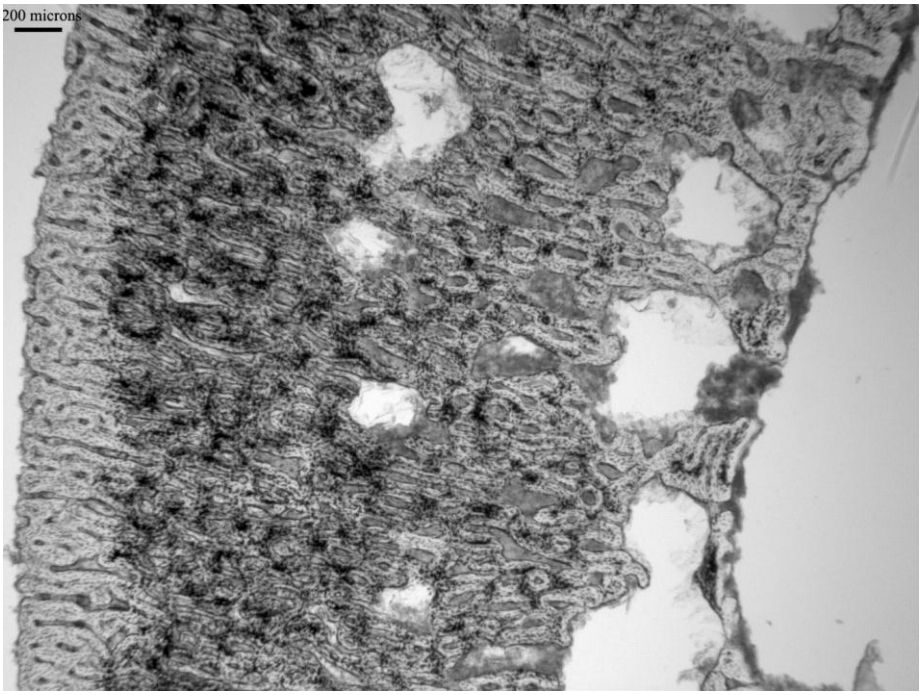

Image 2.19: Micrograph of a transverse femoral thin section from a pig carcass that had been buried for a year by White (2009). The specimen demonstrated high levels of bacterial tunnelling (taken by the author).

White (2009: 183) argued that these findings supported an endogenous origin for early bioerosion of bone. The rapidity and intensity of bacterial invasion and degradation of bone could only be ascribed to the activity of endogenous microbes. The differences in bioerosion between surface-exposed and buried remains suggested that there was a correlation between exposure to putrefaction and osteolytic bacterial attack. The majority of the buried pig remains used in White's (2009) study had not skeletonised, yet their bones demonstrated extensive bacterial tunnelling. Bacterial attack was also observed in bone from the boxed pig remains that had been coated with sterile sand.

None of the bones from the stillborn pigs used in White's (2009) experiment exhibited evidence for bacterial bioerosion (Image 2.20). This observation was not consistent with an exogenous model of decay, as all other categories of remains from the same environments demonstrated some form of microbial alteration. Mammals are born sterile (Mackie 1999). Colonies of bacteria invade and establish themselves within the stomach and intestines a few weeks after birth (Mackie 1999). The lack of internal bacteria means that putrefaction of stillborn and neonatal remains is often delayed or does not occur at all (Polson *et al.* 1985; Janaway 1996; Campobasso *et al.* 2001; Jans *et al.* 2004).The lack of bacterial tunnelling within the bone of the stillborn pigs supported an endogenous model of bioerosion, as these specimens would have not lived long enough to have developed any gut bacteria (White 2009:

177). Histological analysis of human bone thin sections from historical contexts found that lower proportions of neonatal remains were likely to have been affected by bacterial bioerosion than adult bones (White 2009: 154).

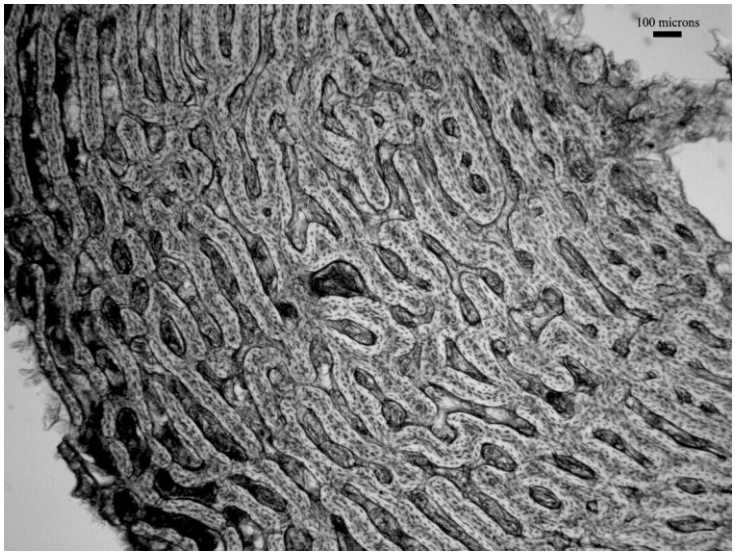

Image 2.20: Micrograph of a transverse femoral thin section of a stillborn piglet that had been buried for one year by White (2009). The specimen was entirely free from bioerosion (taken by the author).

2.2.3.5.5 Bog Bodies & Mummies

Raised bogs are anoxic, acidic, and cold and are characterised by the presence of tannic substances (Painter 1995). These factors produce an environment that is not sympathetic to most species of bacteria. Acidity and the sphagnan chemical secreted by the sphagnum moss deactivate collagenase and protease. Temperatures within a bog are usually lower than what can be tolerated by most species of bacteria. Sphagnan tannins reacts with proteins which causes their molecules to cross-link, rendering them inaccessible to most microbes (Painter 1995). The combination of sphagnum, acidity and anoxia does not produce a sterile environment, although these conditions ensure that the types of soil bacteria adapted to exploiting bodily proteins are mostly absent (Ridgeway *et al.* 1986; Painter 1995). The bone of bog bodies may be pertinent to studies of bone bioerosion as any focal osteoclasia is unlikely to have occurred as a result of external microbial invasion.

Bell *et al.*'s (1996) study of forensic remains included a rib from a human body that had lain in a muskeg bog for 15 months. The internal microstructure of this specimen had been extensively degraded by bacteria. A sheep femur that was included within the study by Fernández-Jalvo *et al.* (2010: 78) had been retrieved from a bog environment and also

demonstrated high levels of internal bacterial attack. The sheep femur had lain on top of the peat bog initially, and Fernández-Jalvo *et al.* (2010) suggested that aerobic exogenous bacteria were able to access their specimen before the bog environment discouraged bacterial exploitation. This explanation was unconvincing given that all other surface-deposited remains from Neuadd showed little or no bacterial alteration (Fernández-Jalvo *et al.* 2010). This argument also contradicted Fernandez-Jalvo *et al.*'s (2010: 80) overall conclusions that aerobic bioerosion is a late-occurring phenomenon.

Brothwell & Bourke (1995) examined the histological integrity of arm and finger bones of one of the Iron Age bog bodies that was recovered from Lindow Moss, Cheshire. They observed 'punched-out holes' within the bone microstructure of these samples that resembled the early stages of bacterial attack (Brothwell & Bourke 1995; Brothwell & Gill-Robinson 2002). The responsible microorganisms must have been endogenous primarily because of the nature of the burial context but also because the skin was preserved and the bone had been continually protected from exogenous incursion (Yoshino *et al.* 1991).

Turner-Walker & Peacock (2008) deposited butchered cow metapodial and flesh within a raised sphagnum bog. After four years the flesh was preserved, but SEM demonstrated that the bone had been chemically demineralised (Turner-Walker & Peacock 2008: 159). No MFD were detected within this sample (Turner-Walker & Peacock 2008: 159). This example may be illuminating with regards to bone bioerosion, as the main difference between these samples and the other bioeroded bog-deposited bones was that Turner-Walker & Peacock's (2008) bone specimens were not buried as part of intact corpses.

The principle that exogenous bacteria would not be able to gain access to fleshed remains suggests that bones from mummified remains may be informative in addressing whether osteolytic bacteria attack from inside or outside the body (Yoshino *et al.* 1991). Most methods of soft tissue preservation involve the circumvention of putrefaction through the removal or neutralisation of gut bacteria (Aufderheide 2003; Lynnerup 2007). Both exogenous and endogenous models of bioerosion would predict that bone microstructure of mummified remains should remain well-preserved. However, if the mummification process was delayed, was not entirely successful, or allowed gut bacteria to remain active for a certain period of time, minor putrefactive bone bioerosion could have occurred. Therefore whilst the lack of focal destruction in mummified bone would be ambiguous with regards to the origin of osteolytic bacteria, any positive identification of MFD must infer invasion by visceral microbiota.

There have been very few histomorphological studies of bone from mummified individuals as the penetration or removal of mummified soft tissue is not considered to be a desirable or ethical process. Histomorphological studies have been conducted on a small but varied number of remains preserved naturally and artificially using a variety of different techniques (Weinstein *et al.* 1981; Thompson & Cowen 1984; Hess *et al.* 1998). All of samples of bone from mummies have demonstrated immaculate levels of histological preservation. This group of isolated reports included a microscopic study of a rib fragment from the naturally-mummified Bronze Age body that was recovered from within a glacier in the Tyrolean Alps (popularly known as Ötzi). No MFD were detected within the rib sample, although species of gut bacteria were preserved within the sub-periosteal region (Hess *et al.* 1998). Endogenous bacteria must have escaped into the bone before their activity was stalled by the freezing environment (Hess *et al.* 1998).

2.2.4 Link between Taphonomy & Bone Diagenesis

There have already been some attempts to use diagenetic parameters to reconstruct the taphonomic histories of bone (Parker Pearson *et al.* 2005; Turner-Walker & Jans 2008; Hollund *et al.* 2012). Different studies have drawn upon divergent models of bone diagenesis and provide separate examples of how bone diagenesis may be used to reconstruct taphonomic events under both endogenous and exogenous models. Those studies that have assumed an endogenous origin for osteolytic bacteria have framed diagenetic change of bone in terms of events that would have affected early bodily decomposition. Those studies that followed an exogenous model of bone bioerosion discuss diagenetic alterations in terms of environmental change over time. The few cases are discussed here alongside attempts to provide alternative explanations of their findings based on opposite models.

2.2.4.1 Endogenous

2.2.4.1.1 Cladh Hallan, South Uist, Outer Hebrides, U.K.

Dating evidence of articulated human remains excavated from underneath house floors at the Bronze Age settlement of Cladh Hallan, South Uist, Outer Hebrides of Scotland suggested that the bodies had originally been buried centuries after death whilst retaining some soft tissue

(Parker Pearson *et al.* 2005; 2007). These analyses suggested that the Cladh Hallan remains had initially been mummified but that burial eventually led to the disintegration of the organic material. Further osteological and DNA analysis supported this conclusion (Parker-Pearson *et al.* 2005).

When the Cladh Hallan bones were examined histologically using thin section light microscopy and HgIP they were found to be well preserved. A thin band of accumulated non-Wedl MFD were located 0.5mm deep to the periosteal surface (Summerfield 2004; Parker Pearson *et al.* 2005) (Image 2.21). The histological structure of a bone taken from an articulated dog at the same site demonstrated extensive bacterial attack (Parker Pearson *et al.* 2005: 541). Parker Pearson *et al.* (2005) concluded that the human bones had been subjected to intense alteration by endogenous gut bacteria which had been suddenly halted. This patterning could not have been the result of processing or excarnation, as the remains were articulated and there was no evidence that the burial contexts had been disturbed or altered by environmental changes such as waterlogging (Parker Pearson *et al.* 2005). The bacterial attack must have been stopped by an anthropogenic process (Parker Pearson *et al.* 2005; 2007). The majority of the other bone samples from similar environments around the site had been severely bioeroded and so the burial environment could not have inhibited intrinsic bone bioerosion (Parker Pearson *et al.* 2005; Mulville *et al.* 2011). The variation in bioerosion between bones obtained from similar burial environments from the site precluded the possibility that bacterial attack was mediated by features of the environment (Parker Pearson *et al.* 2005; 2007; Mulville *et al.* 2011). These findings were consistent with the interpretation of prior intentional mummification of the well-preserved human skeleton (Parker Pearson *et al.* 2005; 2007).

Further histological analysis of the Cladh Hallan bone using FTIR and SAXS revealed that crystallinity towards the periosteal surface of the bone was elevated (Parker Pearson *et al.* 2005: 542). This alteration was not characteristic of microbial degradation but of limited acidic dissolution. The skeleton had been recovered from alkaline machair sands that were unlikely to have encouraged this kind of attack (Parker Pearson *et al.* 2005; Nielsen-Marsh *et al.* 2007). The bones must have been placed originally within a corrosive environment. The closest acidic environment to the settlement was a peat bog. Parker Pearson *et al.* (2005: 542) suggested that the Cladh Hallan bodies were preserved by temporary deposition within a bog which would have preserved the soft tissue and demineralised the periosteal zone (Painter 1995; Parker Pearson *et al.* 2005).

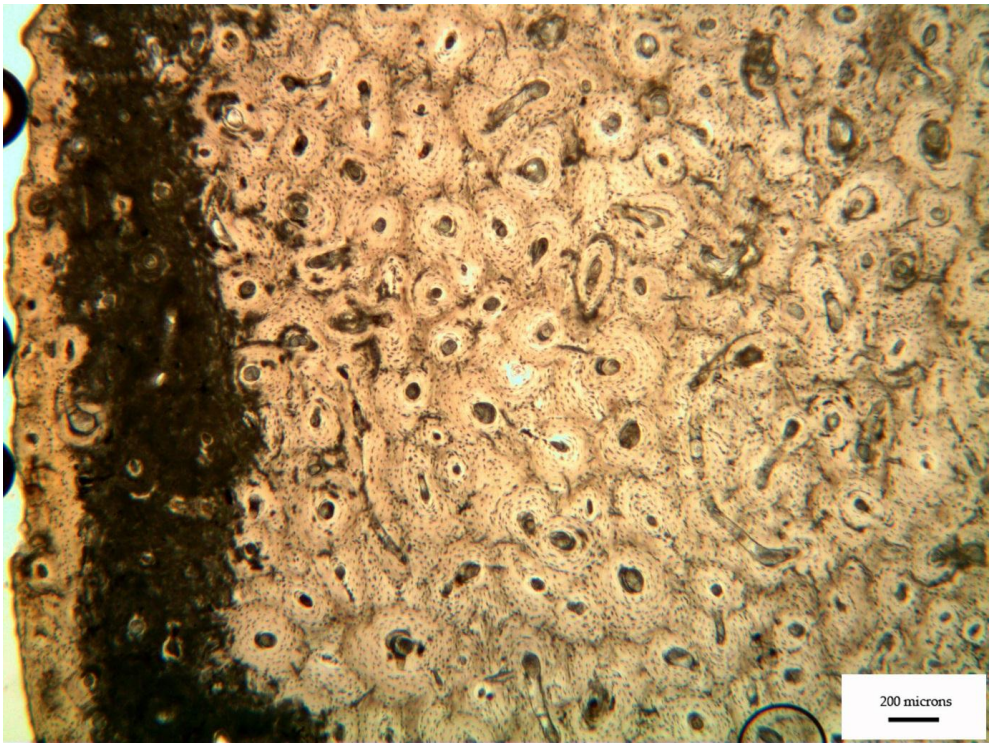

Image 2.21: Micrograph of a transverse femoral thin section from adult male body that was recovered from the Bronze Age Settlement of Cladh Hallan. A minor level of bacterial attack can be observed concentrated at the sub-periosteal region (taken by the author).

It was difficult to explain how an exogenous model of bone bioerosion could explain the patterns observed at Cladh Hallan. Articulated remains from across the site demonstrated highly variable levels of bone bioerosion despite originating from similar depositional environments (Parker Pearson *et al.* 2005; Mulville *et al.* 2011). There was evidence that the mummified Cladh Hallan bodies had originally decomposed within a potentially anoxic environment, which would have prevented aerobic decomposition by soil bacteria. However, prior decomposition within such an environment still does not explain how the bones of the Cladh Hallan mummies came to be only partially bioeroded when most other remains buried within the same environments had been intensively tunnelled by bacteria (Parker Pearson *et al.* 2005; Mulville *et al.* 2011).

2.2.4.1.2 Roman Castricum, The Netherlands

Hollund *et al.* (2012) used endogenous models of bacterial decay to attempt to reconstruct the taphonomic histories of a series of Roman bones excavated from the town of Castricum, in the Netherlands. Thin section light microscopy and transmission electron microscopy were used to

investigate the diagenetic change in each specimen. The majority of the samples were well-preserved and demonstrated no bacterial tunnelling. The presence of pyrite framboid inclusions, orange staining and localised areas of acidic degradation within most of the samples suggested that the burial environment was anoxic during the decomposition of the remains (Bottrell *et al.* 1998; Turner-Walker 1999; Hollund *et al.* 2012). Framboidal pyrite consists of raspberry-shaped particles of iron sulphate (Turner-Walker 1999). Under anoxic conditions enteric sulphate-reducing bacteria encourage the reduction of decomposition products, which react with any available iron to form framboidal pyrite (Turner-Walker 1999). Subsequent aeration causes the framboidal pyrite to oxidise, which lowers pH and promotes localised chemical erosion (Turner-Walker & Jans 2008; Hollund *et al.* 2012).

All of the bones from Castricum had been interred within heavy marine clays (Hollund *et al.* 2012). The density of this type of sediment would have promoted hypoxia or anoxic conditions, which are known to affect autolysis and putrefaction (Polson *et al.* 1985; Gill-King 1997; Turner & Wiltshire 1999; Dent *et al.* 2004; Hollund *et al.* 2012). The burial sediment also lay within the capillary zone of the water table and would have been waterlogged from the point of deposition (Hollund *et al.* 2012). The position of the graves within this zone would have augmented intrinsic anoxia (Mant 1987; Fiedler & Graw 2003; Dent *et al.* 2004). The Roman depositional layer also included a high incidence of humic substances that deactivate proteolytic enzymes and promote cross-linking of the organic material (Painter 1995; van Klinken & Hedges 1995; Nicholson 1998). Bodily decomposition would have been disrupted almost immediately after interment in this type of sediment (Turner & Wiltshire 1999; Hollund *et al.* 2012).The nature of the burial sediments was likely to be responsible for the lack of bioerosion within the Castricum samples (Hollund *et al.* 2012).

One of the bones from an articulated cattle skeleton exhibited some generalised bacterial attack suggesting that it had experienced putrefaction before it was incorporated within the reductive burial environment (Hollund *et al.* 2012: 9). This specimen must have decomposed above ground before it was incorporated into the inhibitive clays (Hollund *et al.* 2012: 9). The bones also showed no staining or pyrite inclusions, which emphasised their differential early *post mortem* history (Hollund et al 2012: 9). This study emphasised that, even under an endogenous model of decay, burial environment still remains an influential factor dictating levels of bacterial bone bioerosion (Hollund *et al.* 2012).

Anoxic environments do not sustain high quantities of the bacteria capable of exploiting bone collagen (Painter 1995). The high level of histological preservation amongst Hollund *et al.*'s

(2012) samples might still have occurred if bone bioerosion was mediated by soil bacteria. However, the bacterial attack found within the bones of the cattle skeleton contradicted an exogenous model of bioerosion. It was unlikely that this skeleton had been exhumed from a primary aerobic burial context that would have allowed for exogenous bacterial exploitation of the bone. This scenario would have required a certain level of skeletonisation to have occurred in order for the soil bacteria to have gained access to the bone. The level of skeletal articulation within the cattle carcass suggested that decomposition had not progressed very far before it was buried within the anoxic clay. The cattle carcass must have decomposed primarily above ground before it was incorporated into the clays. The bones had never been in contact with a soil environment that would have contained abundant levels of osteolytic bacteria. The bacterial bioerosion visible within the bones of this specimen must have been caused by intrinsic organisms.

2.2.4.1.3 Watermead, Leicestershire, U.K.

Collins (2010) performed HgIP analysis on long bone sampled from a disarticulated remain representing at least three individuals that were excavated from a gravel quarry on the Watermead Country Park in Leicestershire in 1994 (Ripper 2010). The remains had been recovered from the spoil heap, but all individuals were represented by only partial skeletons, which suggested that they were not originally deposited as articulated bodies (Ripper 2010). Individual 1 was represented by a cranium, mandible, cervical vertebrae and two possible long bones (Cook 2010). Only a cranium could be allocated to Individual 2 (Cook 2010). The presence of further replicate long bones indicated the presence of a third individual (Cook 2010). The atlas and axis vertebrae associated with Individual 1 demonstrated cut marks indicative of their throat having been cut *peri mortem* (Cook 2010). Radiocarbon dating of the remains placed the death of Individuals 2 and 3 within the Early Neolithic. Bone from Individual 1 dated to the Late Bronze Age (Meadows *et al.* 2010).

HgIP analysis was performed on a right femur associated with Individual 2, a right tibia that may have been associated with Individual 1 and a right clavicle of unknown provenance (Cook 2010). No medium-sized porosities indicative of microbial tunnelling were detected in any of the samples (Collins 2010). This result indicated that none of these samples had not been subject to bacterial bioerosion (Collins 2010). The bones had been recovered from a waterlogged context, which would have interfered with putrefaction, but their disarticulation

suggested that this environment did not represent their primary depositional context (Bottrell *et al.* 1998; Hedges 2002; Collins 2010; Hollund *et al.* 2012). Collins (2010) suggested that the individuals sampled must have been subject to a funerary process that ensured that the bones were not exposed to putrefactive decay, such as excarnation, dismemberment or butchery (Jans *et al.* 2004; Nielsen-Marsh *et al.* 2007).

The lack of bacterial tunnelling within the Watermead specimens could also be explained under an exogenous model of decomposition. The anoxic waterlogged environment would not have maintained populations of aerobic soil bacteria responsible for bone bioerosion under an exogenous model of biodegradation (Painter 1995; Turner-Walker 2008; Turner-Walker & Jans 2008). The disarticulation of the bones suggested that the bodies represented were not originally placed within the context in which they were found. An exogenous model of bioerosion would stipulate that the bones were kept above ground or within a different anoxic environment before they were deposited at Watermead.

2.2.4.2 Exogenous

2.2.4.2.1 Study of Assorted European Remains

Turner-Walker & Jans (2008) used SEM to examine the histological structure of bones excavated from seven archaeological sites in order to reconstruct the environmental changes to their burial environments over time. Their conclusions were based on the presence or absence of pyrite framboids (Bottrell *et al.* 1998; Turner-Walker 1999). A cranial bone of a large mammal recovered from a riverbed in West Runton, Norfolk showed minor peripheral Wedl-tunnelling and some framboidal pyrite formation. The results suggested that the bone was attacked initially by cyanobacteria before being coated with sediment, which produced an anoxic environment (Turner-Walker & Jans 2008: 233). Histomorphological analysis of a Mesolithic human bone from the Vale of Pickering in Yorkshire, England revealed extensive bacterial bioerosion accompanied by pyrite framboids. The bone had probably originally lain in an aerated environment that facilitated attack by soil bacteria before it was buried in anoxic sediment (Turner-Walker & Jans 2008). Turner-Walker & Jans (2008: 233) interpret this pattern as evidence for the bone having initially been exposed on the ground surface before being buried.

A human bone taken from the Ypenburg Neolithic cemetery in the Netherlands demonstrated arrested bacterial decay accompanied by pyrite inclusions. The bone also displayed a high abundance of microfissures. This specimen must have initially been placed in an aerobic well-drained environment that facilitated exogenous bacterial attack before the burial conditions became anoxic (Turner-Walker & Jans 2008: 234). The bacterial attack was so minimal that, rather than the bones having been removed from their original burial context, it was argued that the grave itself must have been rapidly rendered anoxic, probably by waterlogging (Turner-Walker & Jans 2008: 234). This event would have arrested aerobic bacterial attack, encouraged sulphate reducing bacteria and produced an acidic environment that corroded the mineral, which would have caused the extensive microfissuring (Bottrell *et al.* 1998; Turner-Walker & Jans 2008).

These interpretations assumed an exogenous model of bioerosion, but the main findings would still be valid from an endogenous perspective. Exposed remains do not normally demonstrate high levels of bioerosion in their microstructure, which suggested that the Vale of Pickering bones could have been buried immediately and exposed to an anoxic environment via waterlogging or secondary burial (Yoshino *et al.* 1991; Bell *et al.* 1996; Jans *et al.* 2004; Fernández-Jalvo *et al.* 2010; White 2009; Hollund *et al.* 2012). The extensive bioerosion observed in this sample was more commonly found amongst intact articulated burials (Jans *et al.* 2004; White 2009). The bone sample from Ypenburg demonstrated a pattern of bioerosion that was more consistent with the body having been sub-aerially exposed, based on the established link between surface deposition and limited bone bioerosion (Yoshino *et al.* 1991; Bell *et al.* 1996; Jans *et al.* 2004). Episodic waterlogging could still provide a possible explanation for these results, as these conditions encourage organic preservation through the inhibition of microbiological activity (Painter 1995).

2.2.4.2.2 Effects of Heavy Metals

A study by Müller *et al.* (2011) examined bioerosion within butchered bones that had been differentially deposited in burial environments contaminated by bactericidal metals. The bones were recovered from underneath the site of a 14th century metal works in the courtyard of Hôtel de Mongelas in central Paris, France. Eight isolated disarticulated animal bones, consisting of two femora and a humerus from a goat, two tibiae and a radius from a pig, the radius of a cow and a rib of an undefined species were sampled from the site (Müller *et al.*

2011: 48). The study found that bones contaminated with heavy metals such as copper tended to be free from microbial bioerosion (Müller *et al.* 2011: 48). These results suggested that the presence of heavy metals in the soil deters bone bioerosion by exogenous bacteria. However, two of the contaminated bones demonstrated limited levels of internal bacterial attack (Müller *et al.* 2011: 47). This anomalous result was explained by the construction of a latrine at this part of the site during the 18th century (Müller *et al.* 2011: 48). The introduction of organic material and gut microbiota would have recharged the environment with osteolytic microorganisms.

The conclusions of this study were limited by the sample size, the use of bones from different species and from different anatomical elements. The variability in the small number of samples that were chosen meant that the conclusions regarding the variations in bacterial bone bioerosion with metal contamination were tenuous. The use of butchered animal bone meant that these specimens may have been subjected to various undetected taphonomic processes, including cooking, which would have promoted bone bioerosion or affected the bones' susceptibility to bacterial attack. These problems were compounded by the fact that two out of eight of the samples contradicted the central hypothesis regarding the inhibitory effects of heavy metals on osteolytic bacterial activity. The variability in bone bioerosion combined with the small sample size meant that the results could be related to endogenous rather than exogenous microbiota. The explanation for the two anomalous samples makes little sense, as it seems unlikely that toxic contamination of bone would have discouraged one type of bacterial attack but not another.

2.2.5 Conclusion

This review highlights the difficulties in establishing the identity and origins of the bacteria that produce non-Wedl MFD in archaeological bone. Isolated studies often present contradictory results, use low numbers of samples, fail to address the results of other studies or are not repeatable. However, it is argued here that the evidence currently favours an endogenous model of bacterial bone bioerosion. This conclusion is supported by the studies which suggest that bacterial bioerosion occurs early *post mortem*, is linked to early taphonomic events that interfere with a bone's exposure to putrefaction, is highly variable over single sites and consistent sediments, is not related to specific properties of the burial environment, occurs within bones from environments that would not have maintained quantities of exogenous

osteolytic bacteria and is associated anaerobic bacterial species that are predominant within the human gut microbiome (Bell *et al.* 1996, Jackes *et al.* 2001; Jans *et al.* 2004; Guarino *et al.* 2006; Nielsen-Marsh *et al.* 2007; Dixon *et al.* 2009, White 2009; Hollund *et al.* 2012). Specific observations common to the majority of histomorphological studies, such as the clustering of non-Wedl MFD in Haversian systems, their respect for cement lines and their avoidance of the periosteal circumferential lamellar bone all infer an intimate relationship between bacterial attack and vasculature, which is consistent with endogenous origin for invading bacteria (Hackett 1981; Bell *et al.* 1996; Jackes *et al.* 2001; Jans *et al.* 2002; Jans *et al.* 2004; Turner-Walker & Jans 2008; Hollund *et al.* 2012). Studies that have argued for an exogenous origin of osteolytic bacteria have not yet produced results that could not also be explained by the actions of endogenous bacteria.

The persistence of the periosteal bone band as well as the lack of association between measures of bone bioerosion and site environment both contradict predictions of an exogenous model of bacterial attack (Hollund *et al.* 2012). If soil bacteria were able to break down and metabolise the composite bone structure, there has been no explanation as to why they should need to utilise vascular systems to gain access, especially when exogenous fungi are observed to tunnel directly through the periosteal bone surface (Marchiafava *et al.* 1974; Hackett 1981) The studies by Yoshino *et al.* (1996), Fernández-Jalvo *et al.* (2010) and Turner-Walker (2012) are the only ones that report direct evidence that non-Wedl MFD are a late occurring externally-driven phenomenon. However, many of their observations were consistent with an endogenous model of bioerosion. The majority of investigations into this subject are either inconclusive or consistent with an endogenous model that links bacterial bioerosion with putrefaction and early biostratinomy (Yoshino *et al.* 1991; Jans *et al.* 2004; Nielsen-Marsh *et al.* 2007; Fernández-Jalvo *et al.* 2010; White 2009; Hollund *et al.* 2012). Turner-Walker's (2012) experimental study has only limited applicability to bones from temperate Europe, and an endogenous origin of osteolytic bacteria could not be ruled out. An endogenous model of diagenesis forms the basis of the hypotheses that will be tested in the present study.

2.3 FACTORS THAT AFFECT BODILY PUTREFACTION

An endogenous model of bacterial bone bioerosion stipulates that bacterial attack would be controlled by the extent to which the bone was exposed to putrefaction bacteria (Bell *et al.*

1996; Jans *et al.* 2004). Interactions between bone and gut bacteria would be affected by early taphonomic events that either separated the bones from the deleterious bacteria or interfered with natural decomposition (Jans *et al.* 2004; Nielsen-Marsh *et al.* 2007; Hollund *et al.* 2012). The extent to which a particular taphonomic event could curtail putrefactive bone bioerosion would depend on how long after death it was enacted and its effectiveness in neutralising osteolytic visceral bacteria (Jans *et al.* 2004; Nielsen-Marsh *et al.* 2007).

Separation of bacteria from the bone soon after death would provide the best method of ensuring that the bone was not exposed to putrefactive bacterial attack (Bell *et al.* 1996; Jans *et al.* 2004; Nielsen-Marsh *et al.* 2007). The immediacy of these kinds of taphonomic events would ensure that they would take precedence in affecting bacterial bone bioerosion (Bell *et al.* 1996; Jans *et al.* 2004; Nielsen-Marsh *et al.* 2007). A specific set of definable anthropogenic processes could be responsible for this type of event (Jans *et al.* 2004; Nielsen-Marsh *et al.* 2007). The utility of butchery in preventing bacterial bone bioerosion has already been noted (Jans *et al.* 2004; Nielsen-Marsh *et al.* 2007). Processes such as dismemberment and defleshing would have a similar effect. Microbiota rely on the circulatory system and a liquid medium for transmigration, and so early *post mortem* exsanguination might also prevent bacterial bone bioerosion (Bell *et al.* 1996; Zhou & Bayard 2011).

The nature and extent of bodily decomposition is dictated by a plethora of factors (Rodriguez & Bass 1983; 1985; Micozzi 1986; Bass 1987; Mant 1987; Garland & Janaway 1989; Micozzi 1991; Bass 1997; Rodriguez 1997; Sledzik & Micozzi 1997; Mann *et al.* 1990; Manhein 1997; Turner & Wiltshire 1999; Dent *et al.* 2004; Wilson *et al.* 2007; Schotsmans *et al.* 2011; Simmons *et al.* 2011; Ubelaker & Zarenko 2011; Zhou & Bayard 2011; Schotsmans *et al.* 2012). The next section provides a brief synopsis of these factors. This synopsis will provide some justification for the assertion that the practise of particular funerary process in the past could be reflected within patterns of bacterial bone bioerosion, and outline the issues that are likely to aid or obscure attempts to develop a link between bone bioerosion and funerary treatment.

The list of variables discussed here is not exhaustive. Only those factors that have been identified through forensic or experimental investigation are considered. It is unlikely that all variables which can affect bodily decomposition have been identified (Zhou & Bayard 2011). Moreover, there is still uncertainty regarding the precise ways in which certain taphonomic circumstances affect decomposition. Interactions between the effects of known variables can be complex, and many studies have reached contradictory conclusions regarding the exact changes enacted by particular circumstances. This discussion will only include terrestrial

factors that affect decomposition of a cadaver, as the variables that interfere with decomposition in aquatic conditions are not salient to the current study. Most studies of bodily decomposition have not included analysis of bone microstructure, and so the likely effects of each variable on the bacterial attack of the bone had to be extrapolated from the way they affected early bodily decomposition (Table 2.2).

Variable	Effect on Decay Rate
Temperature	5
Access by insects	5
Burial & depth	5
Carnivore/rodents	4
Trauma (penetrating/crushing)	4
Humidity/aridity	4
Rainfall	3
Body size & weight	3
Embalming	3
Clothing	2
Surface placed on	1

Table 2.2: Scores devised by Mann et al. (1990: 104) expressing the factors that were observed to have the largest effect on the rate of human decomposition in experimental and forensic investigations. Higher numbers indicate higher levels of influence.

2.3.1 Environmental Factors

2.3.1.1 Climate

Climate, especially seasonality, is commonly cited as the major factor that accelerates or discourages bodily decomposition (Rodriguez & Bass 1983; Bass 1987; Mann *et al.* 1990; Manhein 1997; Bass 1997; Wilson *et al.* 2007; Meyer *et al.* 2013). The climate controls two factors pertinent to bodily decomposition: temperature and moisture availability (Rodriguez & Bass 1983; Mann *et al.* 1990; Carter *et al.* 2008; Carter *et al.* 2010). All chemical reactions occur more quickly at higher temperatures, including autolytic and bacterial *post mortem* processes (Gill-King 1997). Bacteria function more effectively within warm temperature ranges

(Child 1995a; 1995b; Janaway 1996; Gill-King 1997; Carter *et al.* 2008). Most bacteria have a functional temperature range of between 10°C and 40°C, with an optimal range of between 25°C and 35°C (Janaway 1996). Visceral putrefactive bacteria and their protease enzymes are most functional at around body temperature, whilst their activity usually ceases at temperatures lower than around 10°C (Child *et al.* 1993; Child 1995a; 1995b; Forbes *et al.* 2005). Microbiota are reliant on the presence of a certain level of moisture within their environment for their mobility, the disposal of their waste products and the functionality of their protease enzymes (Janaway 1996; Carter *et al.* 2010). Warmer climates that allow the body to retain an optimal level of moisture will promote faster bodily decomposition (Rodriguez & Bass 1983; Janaway 1996; Carter *et al.* 2010; Zhou & Bayard 2011).

Cadavers that have been left to decompose on the ground skeletonise fastest in the warmer months (Rodriguez & Bass 1983; Mann *et al.* 1990; Meyer *et al.* 2013). This faster rate of decomposition is partly attributable to increased temperatures accelerating bacterial activity and chemical reactions, but is also due to the higher summer abundance of carnivorous insects which promote skeletonisation (Rodriguez & Bass 1983; Simmons *et al.* 2010; Zhou & Bayard 2011). Warm temperatures also promote the mobilisation of putrefactive gases that attract skeletonising fauna (Mann *et al.* 1990).

It is less certain how far seasonal variation affects the decomposition of buried individuals. Seasonal variations in decomposition of buried carcasses in moderate climates are likely to be muted compared with bodies placed above ground, as the climate of a burial environment is relatively constant beyond a certain depth (Manhein 1997; Rodriguez 1997). Burial prevents carnivorous insects active above ground from contributing to skeletonisation (Rodriguez & Bass 1983; Manhein 1997). Mant (1987) observed slight differences in decomposition corresponding with the season of burial within cadavers of individuals killed during the Second World War which had been exhumed from various contexts in Germany. Bodies buried in summer months demonstrated more advanced decomposition (Mant 1987).

Extreme environmental conditions that cause the temperature of a body to fall outside of bacterial tolerances or serve to dry out the soft tissues are liable to curtail bacterial cadaveric decomposition (Galloway *et al.* 1989; Janaway 1996; Galloway 1997). Desiccation of the soft tissues promoted by hot arid conditions starves bacteria of the moisture they require to remain active (Galloway *et al.* 1989; Janaway 1996; Aufderheide 2003). Very cold environments can desiccate the bodily tissues through freeze-drying (Micozzi 1997). The low temperatures of these environments will also curb internal bacterial activity (Janaway 1996;

Micozzi 1997; Aufderheide 2003). Extremes of climate are likely to affect bodily decomposition in buried and sub-aerially exposed bodies in similar ways, as burial soils within these sorts of contexts tend to share the preservative properties of the aerial environment (Aufderheide 2003).

It is uncertain whether climatic differences between sites as well as seasonal variations in cadaveric decomposition at single sites, would have affected the putrefactive bacterial bioerosion of bone. In temperate climates, differences in temperature and moisture content alter the rate rather than the level of putrefaction a bone experiences and would not be expected to have a significant effect on the overall levels of bacterial bone bioerosion. Seasonal changes are more likely to affect bone bioerosion within sub-aerially exposed remains because of the increased abundances of skeletonising insects promoted by warmer months (Rodriguez & Bass 1983). Putrefactive bone bioerosion would be affected by extreme climatic environments that inhibited bacterial activity from an early *post mortem* stage.

2.3.1.2 Anoxic/Waterlogged Conditions

Environments where oxygen is limited (hypoxic) or absent (anoxic) inhibit early bodily decomposition (Janaway 1996; Turner & Wiltshire 1999; Wilson *et al.* 2007; Turner-Walker & Jans 2008; Hollund *et al.* 2012). Burial environments can be intrinsically anoxic if the soil grain size is small and does not leave enough space for particles of oxygen to percolate through the substrate (Janaway 1996; Dent *et al.* 2004). There has been no satisfactory explanation of the effect of an anoxic environment on early bodily decomposition, given that most putrefaction bacteria are anaerobic (Gill-King 1997). It is possible that soft tissue preserved in anoxic environments represents the material that is usually lost through the action of aerobic soil bacteria. However, Turner & Wiltshire (1999: 117) noted that putrefaction specifically was delayed within pig carcasses deposited in anoxic soils. Putrefaction was only initiated when the bodies were exposed to an aerobic environment through exhumation by scavenging carnivores (Turner & Wiltshire 1999: 118).

These observations suggest that an initial oxygenated phase of decomposition is crucial to the initiation of putrefaction. Autolytic reactions may be slowed by anoxic conditions as the functionality of the enzymes involved in cell autolysis may be reduced by the low redox potential of an anaerobic environment (Janaway 1996; Dent *et al.* 2004)**.** An anoxic environment will also inhibit the early decomposition of the soft tissues by endogenous

aerobic bacteria (Janaway 1996; Gill-King 1997). The initial loss of bodily structures via autolysis and aerobic enteric bacterial attack facilitate the transmigration of anaerobic putrefactive microbiota (Polson *et al.* 1985; Gill-King 1997). Therefore, the non-instigation of these primary processes may delay putrefaction until the body experiences an aerobic environment.

Soils can also be rendered anoxic through waterlogging, which saturates the spaces between soil particles that are normally occupied by oxygen molecules (Janaway 1996). Waterlogging of a grave is often episodic and linked to specific environmental conditions that raise the water table or encourage the surrounding sediment to retain water (Janaway 1996). The prolonged survival of soft tissue is characteristic of studies that have investigated cadavers retrieved from aquatic or waterlogged contexts (Cotton *et al.* 1987; Mant 1987; Janaway 1996; Rodriguez 1997; Sorg *et al.* 1997; Gruspier & Pollanen 2000; Anderson & Hobischak 2004; Pakosh & Rogers 2009; Heaton *et al.* 2010; Widya *et al.* 2012).

Waterlogging is more common within soils that retain small grain sizes (Janaway 1996; Carter *et al.* 2010). The density of these environments allows capillary action to persist for longer periods of time (Janaway 1996). A waterlogged anoxic environment interferes with putrefaction through the same mechanisms discussed above. However, anoxia produced by waterlogging would only delay putrefaction had the body been deposited within an environment that was already waterlogged or had become waterlogged within the first few months after death (Hollund *et al.* 2012).

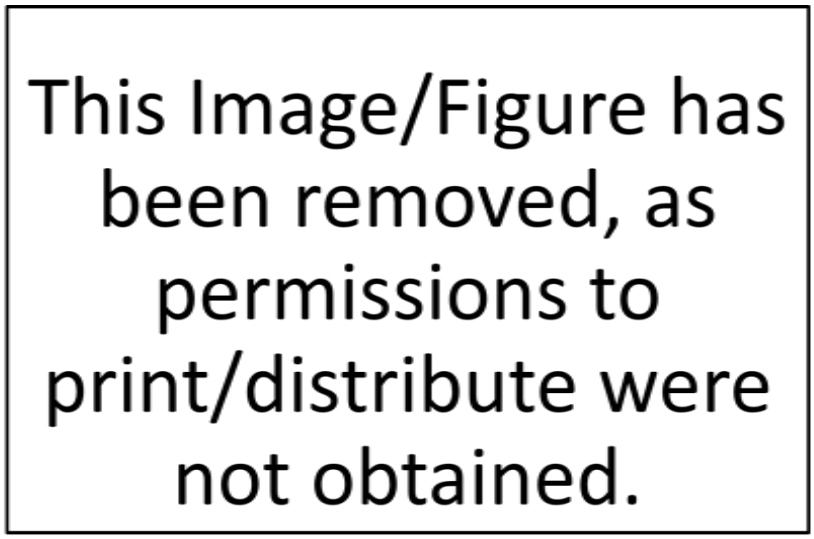

Image 2.22: Photograph of a cadaver from the Medico-Legal Centre of the University of Sheffield demonstrating deposits of adipocere around the skull (Janaway 1996: 71).

The varied survival of soft tissue amongst human remains recovered from waterlogged environments suggests that inundation is capable of preserving a certain amount of soft tissue even after autolysis and putrefaction have been initialised. The preservation of soft tissue in bodies from waterlogged environments is partially attributable to the formation of adipocere (Polson *et al.* 1985; Mant 1987; Janaway 1996; Fiedler & Graw 2003; Ubelaker & Zarenko 2011) (Image 2.22). Adipocere is a waxy substance that is formed though the hydrogenation of body fats by intrinsic (probably non-bioeroding) anaerobic bacteria (Polson *et al.* 1985). Adipocere is difficult for most microorganisms to break down and its formation around the soft tissues may inhibit or reduce putrefactive bacterial activity (Mant 1987; Janaway 1996; Fiedler & Graw 2003). It was originally thought that only sub-cutaneous deposits of fat could be hydrogenated into adipocere. However organs which contain relatively large proportions of fatty tissue, such as the liver and the brain, can also become surrounded by adipocere in the early *post mortem* period (Janaway 1996; Fiedler & Graw 2003). Tissues that do not contain large quantities of fat may be preserved through fat infiltration caused by the extreme pressures produced by putrefaction gases (Fiedler & Graw 2003).

The extent to which adipocere preserves non-adipose tissues is variable (Polson *et al.* 1985; Janaway 1996). Remnants of organs can survive inside accumulations of adipocere, but in other examples only a cast of the original tissue survives (Polson *et al.* 1985; Janaway 1996). Adipocere has been discussed extensively within forensic literature, but the variation and inconsistencies in its occurrence has meant that the exact conditions which promote its formation have yet to be determined (Ubelaker & Zarenko 2011). Adipocere has been found most commonly within bodies deposited in moist anaerobic environments, although it is likely that varied circumstances promote adipocere formation (Fiedler & Graw 2003; Forbes *et al.* 2005; Ubelaker & Zarenko 2011). An excess of environmental moisture is not always necessary. Anaerobic bacteria are capable of reacting with the body's intrinsic moisture. Wet environments accelerate adipocere formation (Forbes *et al.* 2005). If the conditions suitable for sustaining adipocere remain static, the substance can survive for decades or even centuries (Forbes *et al.* 2005; Fründ & Schoenen 2009). However, if a body is placed within a volatile, periodically aerobic environment, then it is likely that any adipocere that formed in the early *post mortem* period would have been lost over the duration of deposition (Forbes *et al.* 2005; Fründ & Schoenen 2009).

The decompositional effects of an anoxic environment can be observed within archaeological human burials recovered from waterlogged environments, which often demonstrate preservation of soft tissue and bodily fluids as well as organic grave goods (Janaway 1996).

However, the variability of adipocere formation and the perseverance of soft tissues other than adipocere suggest that a waterlogged anoxic environment inhibits bodily decomposition in other ways. It is possible that the saturated environment interferes with the functions of anaerobic bacteria or their protease, or otherwise denies the ability of microorganisms to exploit the soft tissues (Painter 1995; Janaway 1996). Waterlogged contexts tend to be acidic due to the types of substances produced by the anoxic fermentative breakdown of organic materials (Child 1995a; Janaway 1996). Acidic environments discourage the growth of most species of bacteria and deactivate collagenase enzymes (Janaway 1996; Forbes *et al.* 2005). Slight acidity may provide one possible explanation for the preservation of non-adipose tissues within waterlogged contexts.

If the depositional environment of a body was anoxic from the point of deposition, than putrefactive bone bioerosion would be expected to have been significantly reduced (Turner-Walker & Jans 2008; Hollund *et al.* 2012). Later interruption of putrefaction via waterlogging, either through adipocere formation or some other means, would also limit the level of putrefactive bioerosion a bone experiences (Janaway 1996). The effect of an anoxic or waterlogged environment on bacterial bioerosion has been studied to some extent (Nielsen-Marsh & Hedges 2000; Turner-Walker & Jans 2008; Hollund *et al.* 2012). These studies support the notion that bone from permanently anoxic sediments will demonstrate little if any bacterial bioerosion, whereas bone from contexts subject to episodic waterlogging will have been subject to limited variable bacterial attack (Nielsen-Marsh & Hedges 2000; Turner-Walker & Jans 2008; Hollund *et al.* 2012).

2.3.1.3 Moisture Content of the Soil

Soil moisture content can affect the rate of decomposition beyond the extreme conditions that promote anoxia (Janaway 1996; Jagger & Rogers 2009; Carter *et al.* 2008; 2010). There is an optimal level of soil moisture that encourages bacterial bodily decomposition (Carter *et al.* 2010). This optimal moisture level fulfils the requirements of exogenous soil bacteria and facilitates their activity during decay (Janaway 1996; Carter *et al.* 2007). Optimal levels of moisture within the burial environment are also likely to promote enteric bacterial decomposition by ensuring that a corpse remains hydrated (Janaway 1996). The decomposition of a cadaver may be related to the matric potential of a burial substrate; how much moisture can be held between the soil particles, which is dependent upon soil texture

and structure. Soils constituted of coarser particles would not support the suspension of water particles above the capillary zone (Janaway 1996; Carter *et al.* 2010). These coarser soils would not facilitate bodily decomposition to the same extent as soils with a denser constitution that keep the body moist (Janaway 1996). Very dry soils are likely to promote the desiccation of the superficial soft tissues (Janaway 1996). However, the relationship between moisture content and bodily decomposition might not be so straightforward. Mant (1987) observed no relationship between moisture content and state of decomposition in buried remains from soils that were not inordinately wet or dry.

Moisture content is more likely to affect exogenous soil bacteria that are involved with the later decay stage of bodily decomposition (Carter *et al.* 2010). It is probable that beyond conditions that promote an anaerobic environment or aridity, soil moisture content would not significantly affect internal putrefaction and any related bacterial bone bioerosion. A low correlation between bacterial bioerosion of bone and soil moisture content in contexts that were not extremely wet or dry was reported by Nielsen-Marsh *et al.* (2000). It is possible that optimal moisture conditions might accelerate endogenous bodily decomposition, although it is unlikely that this process would significantly affect the overall levels of putrefactive attack the bone experiences (Janaway 1996).

2.3.1.4 Soil pH

Most species of bacteria are sensitive to changes in environmental pH (Janaway 1996). Soil pH affects the nature and extent of microbial biomass and the subsequent rate of cadaveric decomposition (Manhein 1997; Haslam & Tibbett 2009). However, the introduction of a putrefying cadaver into the burial environment promotes localised alteration of the chemical properties of the soil, including rises in pH and temperature, creating a cadaver decomposition island (CDI) in the soil (Janaway 1996; Carter *et al.* 2007). These environmental changes are often used as measure of active cadaveric decomposition (Carter *et al.* 2007). The initial rise in pH is probably related to the ammonification of proteins and their subsequent release from decomposing matter (Vass *et al.* 2002; Dent *et al.* 2004; Carter *et al.* 2007; Haslam & Tibbett 2009). The extent and duration of this rise is dictated by the soil environment's buffering capability (Dent *et al.* 2004; Haslam & Tibbett 2009). A decrease in soil pH characterises the later stages of bodily decomposition, associated with the release of organic acids (Dent *et al.* 2004; Haslam & Tibbett 2009).

It is uncertain how far soil pH will dictate the rate of putrefaction, as the only study to have investigated the effects of pH on soft tissue directly used fresh butchered meat (Haslam & Tibbett 2009). High acidity within peat bogs has often been used to explain the soft tissue preservation in bog bodies, as acidic environments can deactivate protease enzymes (Painter 1995; Turner-Walker & Peacock 2008). The intimate relationship between soil pH and bacterial activity ensures that the later decay stages of bodily decomposition will be dictated by pH to some extent (Janaway 1996; Manhein 1997; Haslam & Tibbett 2009). However, the novel internalised nature of the putrefying body, combined with the accompanying alteration of the immediate burial environment, suggest that soil pH would have little effect on putrefaction and related bacterial bone bioerosion (Janaway 1996; Carter *et al.* 2007).

The rapid chemical degradation of bone deposited in acidic contexts suggests that soils which preserve osseous remains over archaeological timescales are unlikely to be very acidic, which would limit any pH-related variation in putrefaction reflected in archaeological bones (Gordon & Buikstra 1981; Bethel & Carver 1987; Nielsen-Marsh *et al.* 2007; Smith *et al.* 2007). This notion is supported by studies by Nielsen-Marsh *et al.* (2007) and Smith *et al.* (2007), which found no correlation between pH of the soil and the extent to which a bone was bioeroded by bacteria.

2.3.1.5 Burial versus Sub-aerial Exposure

Experimental and forensic studies of decomposition in variably inhumed and sub-aerially exposed cadavers from temperate climates have consistently found that skeletonisation of buried remains progresses relatively slowly (Rodriguez & Bass 1983; 1985; Mann *et al.* 1990; Clark *et al.* 1997; Manhein 1997; Rodriguez 1997; Campobasso *et al.* 2001; Dent *et al.* 2004; Matuszewski *et al.* 2008; 2010a; 2010b; 2011; Vass 2011). Cadavers buried in aerobic environment usually take a number of years to skeletonise, whereas a sub-aerially exposed carcass will skeletonise within a few months (Rodriguez & Bass 1983; 1985; Mann et al 1990; Campobasso *et al.* 2001; Breitmeier *et al.* 2005; Simmons *et al.* 2011; Vass 2011). The rate of decomposition amongst exposed carcasses is more variable than within buried examples, primarily because exposed bodies are vulnerable to skeletonisation by a much wider range of faunal and environmental factors (Rodriguez & Bass 1985; Mann *et al.* 1990; Simmons *et al.* 2011; Zhou & Bayard 2011). Exposed bodies also skeletonise rapidly because of the higher

above-ground temperatures, which facilitate faster bacterial growth (Gill-King 1997; Carter *et al.* 2008).

Fauna, particularly insects, often remove the soft tissue and internal organs of an exposed body before the gut bacteria have had chance to complete their full putrefactive cycle (Rodriguez & Bass 1983; 1985; Simmons *et al.* 2010). Blow-fly maggots, which are usually abundant on surface-deposited carcasses, can excrete bactericidal chemicals that may subdue putrefactive activity (Kerridge *et al.* 2005; Huberman *et al.* 2007). Skeletonising animals and insects are less active within a burial environment (Rodriguez & Bass 1985; Mann *et al.* 1990; Manhein 1997; Clark *et al.* 2007). Therefore, bacterially-mediated putrefaction continues unabated within most buried carcasses (Mann *et al.* 1990; Janaway 1996). The lower temperature of the burial environment will ensure that exogenous bacterial activity is slowed compared to that which occurs above ground (Carter *et al.* 2008; Janaway 1996; Gill-King 1999; Zhou & Bayard 2011). However, the exothermic autolytic and metabolic reactions that occur within a putrefying cadaver ensure that its internal temperature remains elevated during initial decomposition (Janaway 1996; Carter *et al.* 2008). A cadaver will eventually cool to the temperature of its burial environment, but by this point the putrefactive microbiota may have already completed their destructive cycle (Janaway 1996; Carter *et al.* 2008).

The factors that variably influence decomposition of sub-aerially exposed and buried bodies suggests that these depositional circumstances are likely to impact on the putrefactive bacterial tunnelling of the internal bone microstructure. The bone of a sub-aerially exposed carcass will have experienced soft tissue decomposition for only a few months, and most of this soft tissue loss would have been perpetuated by extraneous fauna (Rodriguez & Bass 1983; Mann *et al.* 1990; Campobasso *et al.* 2001; Simmons *et al.* 2010; Matuszewski *et al.* 2010a; 2010b; 2011; Vass 2011). The bone of a cadaver buried within an aerobic environment would have experienced the full extent of putrefaction. Therefore, it would be expected that bone from an exposed carcasses would demonstrate only limited levels of bacterial bioerosion, whilst the bones of buried individuals would demonstrate extensive bacterial attack (Bell *et al.* 1996; Jans *et al.* 2004; Fernández-Jalvo *et al.* 2010). This prediction is borne out by experimental and archaeological studies of decomposition and bone bioerosion, which report that human and animal remains skeletonised through sub-aerial exposure demonstrate limited or no levels of bacterial bioerosion (Bell *et al.* 1996; Turner-Walker & Jans 2008; Fernández-Jalvo *et al.* 2010; Hollund *et al.* 2012). In contrast, the majority of buried articulated human archaeological remains usually demonstrate high levels of bacterial attack to their internal microstructure (Nielsen-Marsh *et al.* 2000; Turner-Walker *et al.* 2002; Jans *et al.* 2004; Nielsen-

Marsh *et al.* 2007). White's (2009) histological study of bone from buried and sub-aerially exposed pig carcasses found that the extent of bacterial bioerosion was directly related to the rates of decomposition promoted by their depositional circumstances.

2.3.2 Intrinsic Factors

2.3.2.1 Body Mass

Body mass has been identified as a factor that can affect cadaveric decomposition (Garland & Janaway 1989; Mann *et al.* 1990). Fereira & Cunha (2013: 4) observed that bodily decomposition occurred more rapidly within individuals that had died whilst emaciated, whether through malnutrition, disease or other factors such as drug addiction. Those bodies that had retained larger amounts of body mass took longer to decompose because of the greater abundance of sub-cutaneous fat (Fereira & Cunha 2013). Excessive adipose tissue had often been hydrogenated into adipocere (Ferreira & Cunha 2013).

Similar discrepancies in patterns of decomposition between individuals of variable body size were observed by Mant (1987: 72). Sutherland *et al.* (2013) observed similarly slow rates of decomposition amongst sub-aerially exposed pig carcasses of different sizes, although they attributed this pattern to the volume of soft tissue that had to be removed in each case, rather than the formation of adipocere. However, cadavers that retain a high body mass have also been observed to decompose more rapidly than the bodies of smaller individuals placed within the same environment (Mann *et al.* 1990). In these cases, increased moisture content of fatty deposits encouraged bacterial activity (Mann *et al.* 1990; Clark *et al.* 1997; Campobasso *et al.* 2001). The effects of large amounts of body fat on cadaveric decomposition will probably vary with certain depositional conditions.

It is difficult to say whether the differences in bodily decomposition promoted by variation in body mass would affect putrefaction and related bone bioerosion. Higher body mass has been noted to affect the rate rather than the nature or extent of soft tissue decomposition. It seems likely that bones would be exposed to similar levels of putrefactive bacterial activity regardless of body size (Mant 1987; Garland & Janaway 1989; Mann *et al.* 1990; Fereira & Cunha 2013). The exception may be in cases where large body mass has encouraged the formation and perseverance of adipocere. Adipocere is only likely to form in a way that would affect putrefaction within particular environments and in extreme cases where the individual

retained large amounts of fat (Mant 1987; Fereira & Cunha 2013). It seems unlikely that differences in body mass would have regularly affected putrefactive bone bioerosion.

2.3.2.2 Pathology

Pathological disorders that involve bacterial infection may upset the balance of intrinsic microbiota in a decomposing cadaver (Garland & Janaway 1989; Rodriguez 1997; Campobasso *et al.* 2001; Vass 2011; Zhou & Bayard 2011; Fereira & Cunha 2013). Heightened bacterial load in the blood stream and the organs may increase the rate of bacterial decomposition either through the abundance of deleterious microbiota or the promotion of elevated cadaveric temperatures (Garland & Janaway 1989; Janaway 1996; Zhou & Bayard 2011; Fereira & Cunha 2013). Individuals that are known to have died of bacterial infection have been observed to skeletonise more rapidly than individuals that died of non-bacterial causes (Zhou & Bayard 2011; Fereira & Cunha 2013). Increased rates of putrefaction have also been noted in individuals that had died of significant hyperglycaemia related to *diabetes mellitus* (Zhou & Bayard 2011; Fereira & Cunha 2013). Putrefaction bacteria such as *Clostridium sp.* obtain organic carbon from glucose (Zhou & Bayard 2011). The heightened levels of sugars within the blood of hyperglycaemic individuals facilitate rapid decomposition (Zhou & Bayard 2011).

It is uncertain as to the extent to which particular pathologies will affect the rate of bone bioerosion in line with bodily decomposition. Certain infectious bacteria are capable of attacking the bone substrate in a living individual, but only the inflammatory response of the living tissue has been documented, rather than the micromorphology of any bacterial exploitation. Analysis of *post mortem* blood from individuals that died of specific bacterial infections have failed to identify pathological species, although it was unlikely that all bacterial species present had been cultured successfully (Zhou & Bayard 2011). The consistency in morphologies of MFD observed in archaeological bone suggests that pathological bioerosion, if it does occur, is visually analogous to intrinsic bacterial attack (Hackett 1981). Intrinsic bacteria are capable of completely bioeroding the bone without the input of pathological bacteria. Therefore, in most cases it would be expected that the overall visual signature of bioerosion would differ little between bones from individuals that had variably died from bacterial infection (Hackett 1981; Jans *et al.* 2004) However, if the pathological bacteria do not exploit the bone but are able to outcompete the intrinsic microorganisms in the degradation of the soft tissues, it is possible that bacterial bioerosion of bone would be curtailed (Zhou & Bayard

2011). Diseases that affect the organisation of the bone microstructure, such as Paget's disease or osteoporosis, could affect the logistics of bacterial invasion of the bone, which may have repercussions on the extent and morphology of bioerosion (Bell & Jones 1991; Boyce 1993; Schultz 1993). No studies have ever investigated this question, and so the exact effects of such pathologies cannot be known.

2.3.3 Anthropogenic Factors

2.3.3.1 Clothing & Wrapping

The presence of clothing or wrappings is often observed to influence bodily decomposition, but the their effects are complex, variable and dependent on a combination of environmental factors (Mant 1987; Garland & Janaway 1989; Galloway *et al.* 1989; Mann *et al.* 1990; Goff 1992; Aturaliya & Lukasewycz 1999; Campobasso *et al.* 2001; Fielder & Graw 2003; Kelly *et al.* 2009; Vass 2011; Voss *et al.* 2011; Fereira & Cunha 2013). Certain types of wrapping and clothing can aid in the desiccation of soft tissues and slow down visible decomposition through the rapid absorption of moisture from the skin surfaces (a wicking effect) (Galloway *et al.* 1989; Aturaliya & Lukasewycz 1999). Wrappings can also serve to arrest decomposition in bodies exposed on the ground surface through the prevention of entomological access (Goff 1991; 1992; Campobasso *et al.* 2001).

The presence of clothing has also been observed to increase the rate of decomposition in bodies exposed to sunlight (Mann *et al.* 1990; Aturaliya & Lukasewycz 1999; Kelly *et al.* 2009; Voss *et al.* 2011). Skeletonising maggots utilise wrappings or clothes to shield themselves from the sun (Mann *et al.* 1990; Aturaliya & Lukasewycz 1999; Kelly *et al.* 2009; Voss *et al.* 2011). In wet environments, the absorption of moisture by clothing or wrappings encourages adipocere formation by retaining water close to the surface of the body (Mant 1987; Kelly *et al.* 2009; Voss *et al.* 2011; Fereira & Cunha 2013). The progressive formation of adipocere may decelerate endogenous and exogenous bacterial decomposition (Mant 1987; Aufderheide 2003; Forbes *et al.* 2005). Synthetic materials are most efficient in encouraging the formation of adipocere (Mant 1987; Fereira & Cunha 2013).

These observations suggest that wrapping or clothing augment soft tissue preservation encouraged by specific environmental conditions (Mant 1987; Galloway *et al.* 1989; Aturaliya & Lukasewycz 1999). The likelihood that high numbers of archaeological skeletons were buried

clothed or wrapped, combined with the paucity of adipocere from the archaeological record, would suggest that this substance is unlikely to have affected decomposition within wrapped remains from most burial environments. However, adipocere which formed in the early *post mortem* period may have decomposed over the archaeological timescales (Ubelaker & Zarenko 2011).

It is difficult to determine to what extent or how often the presence of wrappings or clothing would affect putrefaction in a way that interfered with bacterial bone bioerosion. Adipocere may compromise internal bacterial activity, but this substance is only likely to appear under specific environmental conditions which would already be liable to affect putrefaction and bacterial bone bioerosion (Mant 1987; Forbes *et al.* 2005; Turner-Walker & Jans 2008; Ubelaker & Zarenko 2011). Burial environments which promote adipocere formation, such as those with high moisture content, will interrupt putrefaction regardless of whether the body was wrapped (Mant 1987; Fielder & Graw 2003; Forbes *et al.* 2005; Carter *et al.* 2010; Ubelaker & Zarenko 2011; Vass 2011). It is unlikely that wrapping would have significantly affected putrefactive bone bioerosion in archaeological remains that had not experienced these conditions.

Soft tissue preservation promoted by clothing through desiccation is limited to the skin, and does little to prevent internal putrefaction (Galloway *et al.* 1989). The protection afforded to skeletonising insects by clothing in sub-aerially exposed remains might further minimise bone exposure to putrefaction (Mann *et al.* 1990; Aturaliya & Lukasewycz 1999; Kelly *et al.* 2009; Voss *et al.* 2011). However, clothing or wrapping that surrounded a sub-aerially exposed cadaver may have a prohibitive effect on insect skeletonisation, in which case the bone of a cadaver would be exposed to extensive putrefactive bacterial attack (Goff 1991; 1992; Campobasso *et al.* 2001). The lack of correlation between bacterial bone bioerosion and clothing may be supported by the findings of Jans *et al.* (2004) and Nielsen-Marsh *et al.* (2007) that the majority of bone sampled from articulated archaeological human skeletons demonstrates consistently high levels of putrefactive bioerosion. The samples used in these projects originated from a wide variety of archaeological sites across Europe, which would have included remains that had been variably buried with clothing or wrappings. The lack of variation in bone bioerosion amongst these samples suggests that putrefactive bioerosion was not significantly affected by variation in clothing or wrappings.

2.3.3.2 Burial Depth

The temperature of burial soil is relatively constant when compared to variations above ground (Rodriguez & Bass 1985; Mant 1987; Mann *et al.* 1990; Campobasso *et al.* 2001; Wilson *et al.* 2007; Vass 2011). However, the lower temperatures found at more extreme burial depths in temperate locations can affect bacterial activity and bodily decomposition (Rodriquez & Bass 1985; Janaway 1996; Gill-King 1999; Campobasso *et al.* 2001; Wilson *et al.* 2007). Most species of bacteria cannot tolerate temperatures lower than 4^{o}C (Janaway 1996; Gill-King 1999). Low burial depth can significantly retard bacterial decomposition (Rodriguez & Bass 1985; Micozzi 1986; Mant 1987; Janaway 1996; Gill-King 1999).

The oxygenation of the soil also decreases with burial depth depending on its consistency (Dent *et al.* 2004; Vass 2011). The hypoxic or anoxic conditions present at certain burial depths will interfere with bodily decomposition (Janaway 1996; Dent *et al.* 2004; Vass 2011; Gill-King 1997) (Figure 2.6). Anoxic conditions can be produced if a grave lies below the capillary fringe of the water table, where the soil is saturated (Dent *et al.* 2004; Hollund *et al.* 2012). Burial depth will interact with changes in the height of the water table in dictating the rate and nature of bodily decomposition.

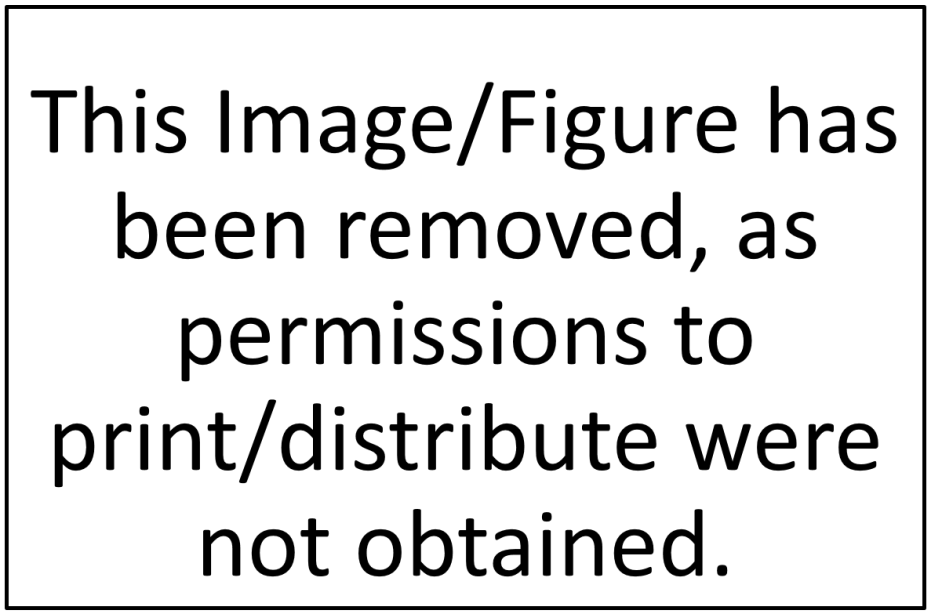

Figure 2.6: Diagram illustrating the amount of oxygen available at different burial depths (Dent et al. 2004: 578).

Shallow burial provides scavengers and certain insects with greater access to a decomposing cadaver (Rodriquez & Bass 1985; Mann *et al.* 1990; Campobasso *et al.* 2001; Schotsmans *et al.*

2011). In temperate climates, the upper soil layers are more aerated and warmer than those below, and promote increased bacterial activity (Rodriguez & Bass 1985; Janaway 1996; Dent *et al.* 2004). The environment of shallow burials is more influenced by variable climatic conditions above ground. It is likely that rate of decomposition amongst shallowly-buried deposits will be more diverse and linked to changes in climate (Rodriquez & Bass 1985; Rodriguez 1997). Variation in the effects of different soils means that there is no constant method of defining what classes as a shallow or deep burial in a way that would relate to bodily decomposition (Rodriguez & Bass 1985; Rodriguez 1997; Vass *et al.* 2011). Deep burials are usually considered to be those that lie over two metres below the original ground surface, whereas shallow burials have been classified as those which lie within the first fifty centimetres of soil (Rodriguez & Bass 1985; Rodriguez 1997; Vass *et al.* 2011). Bodies buried this shallowly will be accessible to skeletonising insects (Rodriguez & Bass 1985; Schotsmans *et al.* 2011; Vass *et al.* 2011). However, the overall effects of different burial depths on decomposition will vary with soil composition, access afforded to insects, moisture content and bacterial load (Rodriquez & Bass 1985; Janaway 1996; Campobasso *et al.* 2001; Wilson *et al.* 2007; Schotsmans *et al.* 2011; Vass *et al.* 2011).

Decomposition rates of bodies placed at moderate burial depths are likely to vary although the overall levels of putrefactive bioerosion the bones experience would be similar (Rodriguez & Bass 1985; Breitmeier *et al.* 2005). The decomposition of bodies buried at extreme depths or within the capillary fringe is likely to have been arrested early on, which would have an effect on the extent of putrefactive bone bioerosion (Turner-Walker 2008; Hollund *et al.* 2012). The effect of shallow burial on bone bioerosion would be dependent on whether skeletonisation was dictated by enteric bacteria or external fauna. If external fauna and microbiota were able to remove significant soft tissue before putrefaction was completed, then it is possible that putrefactive bone bioerosion would have been affected. However, the warmer environment of a shallow burial would ensure that the rate of putrefaction remained higher for longer (Rodriguez & Bass 1985; Gill-King 1997; Wilson *et al.* 2007; Schotsmans *et al.* 2011). Putrefactive bioerosion within bones of shallowly-buried cadavers might be expected to vary depending on the season of deposition and accessibility to particular types of fauna. Differences in the rates of decomposition within partially-buried single bodies have suggested that the rate and nature of skeletonisation in shallowly-buried individuals is likely to be in-between levels of decomposition promoted by burial and sub-aerial exposure (Wilson *et al.* 2007; Schotsmans *et al.* 2011). By extension, it is probable that bones from shallowly-buried bodies would demonstrate variable middling patterns of putrefactive bone bioerosion.

2.3.3.3 Coffin Burial

The effect of coffin burial on bodily decomposition is dictated by the nature of the container (Rodriguez & Bass 1985; Garland & Janaway 1989; Mant 1987; Mann *et al.* 1990; Owsley & Compton 1997: Fielder & Graw 2003; Fereira & Cunha 2013). Burial within a sealed, airtight cast iron coffin produces a unique anoxic environment that arrests bodily putrefaction at an early stage (Garland & Janaway 1989; Gill-King 1997; Owsley & Compton 1997). Normal putrefaction continues once a coffin is breached and the environment becomes aerated (Owsley & Compton 1997). These observations suggest that anoxic environments prevent or limit early *post mortem* changes to the body which anaerobic visceral putrefactive bacteria rely on for their proliferation (Gill-King 1997). Coffins constructed out of bactericidal substances such as lead may also inhibit internal bacterial activity (Owsley & Compton 1997).

Most wooden coffins used in the past in Britain were not built to be airtight and would not be expected to inhibit bodily putrefaction in the ways discussed above. However, there are some suggestions that unsealed wooden coffins can interfere with the normal decomposition processes (Mant 1987; Mann *et al.* 1990; Fielder & Graw 2003; Vass 2011). Mant (1987: 67) noted that decomposition amongst individuals interred in coffins was notably accelerated. Coffined bodies also demonstrated much lower frequencies of adipocere than those that had been buried in the soil (Mant 1987: 67). Many of the coffins had been packed with wood shavings, and Mant (1987**:** 68) suggested that this packing may have accelerated putrefaction by promoting increased local temperatures. The wood shavings may have absorbed fluids, which would have deprived internal bacteria of moisture and affected the formation of adipocere (Mant 1987**:** 68)**.** Buried coffins retain a limited quantity of oxygen, which would aid bacterial decomposition in hypoxic or anoxic soils (Mant 1987; Dent *et al.* 2004).

Ferreira & Cunha (2013) observed that decomposition of remains interred within coffins had often been arrested, usually through the formation of adipocere. Many of the burial contexts examined by Fereira & Cunha had also been waterlogged. The coffins retained water more effectively than the burial sediment, therefore coffin burial ensured that anoxic environments promoted by waterlogging persisted for longer. The persistence of these localised environments within coffins was probably responsible for the increased occurrence of adipocere. Fielder & Graw (2003) suggested that different types of wood used in coffins affect bodily decomposition. Adipocere is more likely to form on bodies in coffins made of oak rather than spruce, although there was no explanation provided as to why this was so (Fielder & Graw 2003).

Interment within a sealed airtight coffin has an immediate effect on bodily decomposition, and would be expected to arrest putrefactive bone bioerosion (Owsley & Compton 1997; Gill-King 1997). The exact effect of a wooden unsealed coffin on putrefactive bone bioerosion is more uncertain. The results of the studies discussed above suggest that these types of coffins, like shrouds and clothing, only serve to augment the effects of particular environments that promote the preservation of organic tissue (Mant 1987; Fereira & Cunha 2013). Coffin burial is identified frequently within the archaeological record, but is rarely observed to promote the preservation of soft tissues outside of waterlogged environments. Burial in an unsealed wooden coffin does not appear to consistently affect bodily decomposition. It is likely that some of the Holocene archaeological human bones sampled by Jans *et al.* (2004) and Nielsen-Marsh *et al.* (2007) had been buried within coffins, yet the majority of these samples demonstrated consistent patterns of bacterial bioerosion. It would be expected that burial within a wooden coffin would not have significantly affected putrefactive bone bioerosion in most circumstances.

2.3.3.4 Grave Goods

The presence of bactericidal metals within the burial environment will affect the progression of cadaveric decomposition and bone bioerosion through poisoning of enteric and exogenous microbiota (Garland & Janaway 1989; Janaway 1996; Müller *et al.* 2011). There is evidence for this effect within bodies interred within coffins constructed out of bactericidal substances such as lead (Janaway 1996; Owsley & Compton 1997). However, these studies suggest that bodily putrefaction is only arrested if these substances are abundant within the environment and lie close to the body. Only a small proportion of grave goods will have been constructed out of bactericidal substances and an even smaller proportion of these items would have lain in contact with the body during its decomposition. Therefore it is unlikely that grave goods would have significantly interfered with bodily decomposition and putrefactive bone bioerosion in most situations.

2.3.3.5 Embalming & Mummification

The definition of embalming can vary, but in the present study it is defined as the intentional application of substances to a body in order to preserve the soft tissues for a set or indefinite

period of time (Sledzik & Micozzi 1997; Aufderheide 2003). The substances that are used in embalming are usually bactericides or desiccates (Aufderheide 2003). Embalming staves off decomposition by circumventing putrefaction through the neutralisation of enteric microbiota (Aufderheide 2003). All methods of embalming are temporary (Aufderheide 2003). Embalmed bodies will succumb to natural exogenous decay unless they are continually subject to preservative measures or environments (Mann *et al.* 1990; Aufderheide 2003). For instance, the body of the 17th century A.D. Italian saint Francesco Caracciolo had skeletonised by the time it was recovered from Agnone, in the Abruzzo region to the city of Naples in the 20th century A.D., despite there being documented evidence for the body having been successfully embalmed (Rasmussen *et al.* 2012).

All studies of decomposition in embalmed remains have used bodies that were preserved by modern Western methods (Mann *et al.* 1990; Sledzik & Micozzi 1997; Lynnerup 2007). Modern embalming is usually achieved through the replacement of bodily fluids with preservative chemicals such as formaldehyde (Sledzik & Micozzi 1997; Aufderheide 2003). This process is commonly performed to ensure that a body remains presentable for funeral, particularly if it is being transported over a long distance (Aufderheide 2003). These methods of embalming are engineered to temporarily prevent or sufficiently slow down putrefaction between death and the funeral. It is probable that autolysis and putrefaction continue to some extent within these bodies, but at a much reduced rate (Mann *et al.* 1990; Sledzik & Micozzi 1997; Aufderheide 2003). Decomposition of embalmed bodies subsequent to burial is slow and deviates from the patterns observed within non-embalmed cadavers (Mann *et al.* 1990). However, studies of buried bodies from 19th and 20th century USA have indicated that modern embalmed bodies will eventually skeletonise (Mann *et al.* 1990). Parts of the body that contain large amounts of tissue, such as the buttocks and thighs, are less effectively penetrated by embalming fluids and are usually amongst the first to decompose (Mann *et al.* 1990). It is possible that the negative effect of the embalming process on enteric gut bacteria ensures that decomposition of these cadavers is mediated almost entirely by exogenous bacterial decay (Mann *et al.* 1990; Sledzik & Micozzi 1997). There may be slight variations observed in the extent of enteric putrefactive bacterial attack depending on the quality and timing of embalming.

Mummification refers to any natural or artificial process that preserves bodily soft tissues, including embalming (Aufderheide 2003; Lynnerup 2007). Most mechanisms of mummification are temporary, and soft tissue will eventually be lost unless there are renewed attempts at preservation, or the body is placed within an environment that is conducive to soft tissue preservation (Aufderheide 2003). Like embalming, most anthropogenic methods of

mummification involve attempts to circumvent putrefaction through the neutralisation of visceral bacteria (Aufderheide 2003). Mummification can also occur naturally as a result of processes that kill enteric bacteria or transform the soft tissue into a substance that is more difficult for microbes to break down (Painter 1995; Aufderheide 2003; Forbes *et al.* 2005; Lynnerup 2007). The transformation of sub-cutaneous fat into adipocere can be classified as a form of mummification, although the frequency and extent of adipocere formation over single bodies tends to be variable (Forbes *et al.* 2005; Fielder & Graw 2003; Lynnerup 2007; Ubelaker & Zarenko 2011).

Artificial methods of mummification such as embalming or evisceration directly target the putrefactive process and would limit bacterial bioerosion (Aufderheide 2003; Lynnerup 2007). Natural mechanisms of mummification usually affect the superficial bodily tissues, and do not often prevent internal putrefaction (Aufderheide 2003; Lynnerup 2007). Internal putrefaction is only affected in extreme cases where transformation of external and internal soft tissue occurs rapidly (Aufderheide 2003; Lynnerup 2007). Natural mummification would be expected to variably limit putrefactive bone bioerosion, depending on the timing and mechanism of preservation. Conditions that promote preservation of only the superficial soft tissues would be expected to have a nuanced effect on putrefactive bone bioerosion. The few histomorphological studies of bone from individuals that were mummified by natural processes have consistently failed to locate any MFD (Weinstein *et al.* 1981; Thompson & Cowen 1984; Brothwell & Bourke 1995; Hess *et al.* 1998). All of these samples had been taken from remains that had been mummified by processes that would have had an immediate effect on putrefaction.

2.3.3.6 Indoor Environments & Caves

Different non-burial environments affect cadaveric decomposition in variable ways. Structures obstruct skeletonising carnivores and insects (Galloway *et al.* 1989; Goff 1991; Anderson 2011; Vass *et al.* 2011). Indoor bodily decomposition proceeds at a slower rate than outdoor decomposition, as indoor decomposition is mostly mediated by the action of endogenous microbiota (Goff 1991; Anderson 2011; Vass *et al.* 2011). Insect colonisation is also reduced in enclosed environments because of the containment of putrefactive odours (Mann *et al.* 1990; Goff 1991; Anderson 2011). Decomposition of bodies within modern indoor environments is often complicated by factors such as central heating or pets, which serve to alter the rate and

the nature of soft tissue loss (Zhou *et al.* 2011). Factors relating to indoor decomposition tend to delay, rather than prevent the initiation of entomological soft tissue loss. The extent of putrefaction and related bacterial bone bioerosion within a body placed in such an environment would be predicted to lie between that observed within buried and sub-aerially exposed remains (Goff 1991; Anderson 2011).

Caves are unique depositional environments and their properties ensure that decomposition of a cadaver would be affected by factors common to both subterranean and sub-aerial contexts (Terrell-Nield & MacDonald 1997). Temperatures within caves are usually lower than those outside and more similar to the burial environment. Caves are resistant to fluctuations in the outside temperature (Terrell-Nield & MacDonald 1997). The cooler cave environment would ensure that putrefactive bacterial activity and the progression of bone bioerosion would be slowed within a cave-deposited cadaver (Mann *et al.* 1990; Gill King 1997; Terrell-Nield & MacDonald 1997). However, cave-deposited cadavers would be more susceptible to faunal skeletonisation, disturbance and disarticulation than buried bodies. An experimental study of decomposition in rat cadavers within a cave environment found that whilst insects contributed to soft tissue loss, their activity was reduced compared to what is observed within sub-aerially exposed bodies (Terrell-Nield & Macdonald 1997). Sub-aerially exposed bodies normally skeletonise within a few months (Rodriguez & Bass 1983). Skeletonisation of the cave-deposited cadavers was variable but often took a number of years (Terrell-Nield & MacDonald 1997). Reductions in insect activity correlated with distance from the entrance of the cave (Terrell-Nield & Macdonald 1997: 56). Insects are cold blooded, and the low temperatures of the cave environment may have discouraged their activity within the cave. Low temperatures would also reduce insects' metabolic rate (Terrell-Nield & MacDonald 1997).

The cave would have limited the diffusion of putrefactive odours that attract saprophytic invertebrates (Goff 1991; Terrell-Nield & MacDonald 1997; Anderson 2011). Cadavers placed near the entrance were exposed to higher levels of insect activity, but often desiccated due to the increased temperatures and air movement. The nature of bodily decomposition within a cave environment was similar to an indoor context and lay somewhere in-between the prolonged bacterially-mediated processes encouraged by a burial environment and the rapid, entomological skeletonisation of sub-aerially exposed cadavers (Rodriguez & Bass 1983; 1985; Terrell-Nield & MacDonald 1997). Bones from a cave-deposited body are likely to have been exposed to variable medium levels of putrefactive bioerosion, depending on the part of the cave where they decomposed.

2.3.3.7 Trauma

Human cadavers that demonstrate evidence for previous penetrative trauma have been observed to decompose more rapidly than those without injury (Micozzi 1986; Mant 1987; Garland & Janaway 1989; Galloway *et al.* 1989; Mann *et al.* 1990). Such trauma allows exogenous fauna and microbiota easier access to the insides of a cadaver, which allows exogenous decay to augment endogenous putrefaction at an earlier stage. This effect produces faster rates of skeletonisation (Micozzi 1986; Mant 1987; Galloway *et al.* 1989; Garland & Janaway 1989; Mann *et al.* 1990). Penetrative trauma may also provide increased access to skeletonising insects. Mann *et al.* (1990) observed that flies were attracted to and laid eggs around the areas of trauma within a cadaver, which promoted faster rates of skeletonisation.

However, Cross & Simmons (2010: 300) recorded that real-time decomposition of pig cadavers did not correlate with the presence of penetrative trauma. There was no increased entomological activity observed around the areas of trauma in these remains (Cross & Simmons 2010: 300). These results suggested that the relationship between penetrative trauma and the rate of bodily decomposition is complex and influenced by interactions with other environmental factors (Bachmann & Simmons 2010; Cross & Simmons 2010). The extent to which penetrative trauma would be expected to have affected bone bioerosion would be dependent upon how far the increased exogenous invasion upset internal enteric putrefaction. If the decomposition of the soft tissues was mostly mediated by exogenous factors, then bone bioerosion might be limited. It is difficult to say whether this scenario is likely, as exogenous infiltration might not upset endogenous bone bioerosion and the evidence surrounding the relationship between decomposition and penetrative trauma is contradictory.

2.3.4 The Use of Bone Bioerosion in Detecting Funerary Processes

Anthropogenic processes that result in the removal of the bone from the visceral microbiota, such as butchery, defleshing, disarticulation and dismemberment, are likely to have the largest inhibitory effect on putrefactive bone bioerosion (Jans *et al.* 2004; Nielsen-Marsh *et al.* 2007). (Jans *et al.* 2004; Nielsen-Marsh *et al.* 2007). There is good reason to suggest that mortuary rites which involved any of these processes would produce characteristic signatures of putrefactive bone bioerosion. Discussion of the factors that affect bodily decomposition suggested two further circumstances that are likely to interfere with putrefactive bone

bioerosion: sub-aerial exposure and mummification (Rodriguez & Bass 1983; Aufderheide 2003; Lynnerup 2007). Both of these processes can occur as a result of natural influences, but have sometimes been utilised in the anthropogenic treatment of remains (Galloway *et al.* 1989; Aufderheide 2003; Lynnerup 2007; Huchet & Greenberg 2010)

The human urge to retrieve the dead and afford them some form of ritual treatment means that sub-aerial exposure of most human remains usually represents part of a formalised mortuary ritual (Parker Pearson 1999). By itself, this process is likely to eventuate in the complete destruction of bones through weathering (Parker Pearson 1999). Spontaneous natural mummification of the kind that would affect putrefactive bone bioerosion occurs rarely within bodies deposited in temperate climates (Aufderheide 2003; Lynnerup 2007). Mummification of human remains from temperate environments would be most likely to have occurred as a result of intentional anthropogenic treatment. Certain anthropogenic process enacted as part of mortuary rites, such as coffin burial or wrapping, have some influence on bodily decomposition (Mant 1987). However, the subtlety of the influence of these factors on cadaveric decomposition suggest that they would not have had a significant effect on putrefactive bone bioerosion.

Studies by Turner-Walker *et al.* (2002), Jans *et al.* (2004) and Nielsen-Marsh *et al.* (2007) have suggested that articulated burial soon after death is characterised by extensive putrefactive bioerosion to the internal bone microstructure. These observations are cogent given that burial of an intact body within aerobic soils is likely to expose the bones to the maximum levels of putrefaction (Rodriguez & Bass 1983; 1885). Consistent poor histological preservation of buried articulated skeletons would provide the perfect comparison to bones from bodies treated in ways that would have limited their exposure to putrefaction and would justify the use of bone histology for inferring funerary treatment. However, innumerable environmental and anthropogenic factors can affect the decomposition of a buried body (Rodriguez & Bass 1985; Mant 1987; Mann *et al.* 1990; Manhein 1997; Rodriguez 1997; Dent *et al.* 2004; Vass 2011). An anoxic burial environment affects both putrefaction and bone bioerosion (Polson *et al.* 1985; Turner & Wiltshire 1999; Dent *et al.* 2004; Turner-Walker & Jans 2008; Hollund *et al.* 2012).

Other environmental and anthropogenic factors may affect bodily putrefaction and bone bioerosion in unknown variable ways and obfuscate any signatures of anthropogenic treatment. However, studies of the way in which these factors affect bodily decomposition suggest that is unlikely that most would significantly interfere with putrefactive bioerosion. For

instance, seasonality has the largest overall impact on the rate of bodily decomposition, but bones from bodies that decomposed at different times of year are likely to have been exposed to similar overall levels of putrefactive bioerosion, albeit at different rates (Rodriguez & Bass 1983; 1985; Mann *et al.* 1990; Campobasso *et al.* 2001; Vass 2011). These inferences of how certain variables were likely to have affected putrefactive bone bioerosion were extrapolated from experimental and forensic studies of decomposition and are therefore tenuous. At present, it is unknown whether bone bioerosion reflects very early taphonomic processes that had a direct effect on putrefactive decay, or the effects of a plethora of different factors that variably interfered with bodily decomposition until skeletonisation. The purpose of the current study is to establish whether the link between the most influential anthropogenic treatments and bacterial bone bioerosion is detectable amongst the potential noise from all other factors that can influence bodily decomposition.

Only a limited selection of funerary processes are likely to have affected putrefaction in a way that would have left a characteristic signature of bacterial bone bioerosion (Table 2.3). In addition, it is likely that different forms of treatment would produce similar microstructural signatures of decay. It is not the contention of the current study that bioerosion alone can be used to infer treatment, only the extent to which the bone was exposed to putrefaction, which is likely to be controlled by early taphonomic processes (Jans *et al.* 2004; Nielsen-Marsh *et al.* 2007). If it is established that bacterial bone bioerosion relates to nearly *post mortem* treatment in predictable ways, then measures of the extent to which the bone was exposed to putrefaction could be combined with other contextual taphonomic evidence to produce more precise reconstructions of the early *post mortem* treatment of individuals in the past.

Treatment	Bioerosion
Dismemberment	None
Defleshing	None
Evisceration	None
Mummification	Limited/None
Sub-aerial exposure	Limited
Burial	Severe

Table 2.3: Speculative list of the types of anthropogenic funerary treatments that are likely to affect putrefactive bone bioerosion alongside details of their predicted effects based on the author's assessment of models of decomposition.

Relationships between early anthropogenic taphonomic events and bone bioerosion would be useful for discerning between different funerary treatments that produce similar archaeological records. For instance, assemblages of disarticulated human bone may have been accumulated through defleshing by primary burial, sub-aerial exposure or dismemberment (Parker Pearson 1999). There have been several attempts to characterise the nature of the assemblages produced by each of these processes in order to aid their identification in the archaeological record (Mays 1998; Carr & Knüsel 1997; Craig *et al.* 2005; Outram *et al.* 2005; Smith 2006; Redfern 2008). For instance, skeletal part representation is often used to identify whether an assemblage had primarily decomposed in a different context (Mays 1998). The smaller bones of the hands and feet disarticulate quickly and would be more likely to have been missed when the partially-decomposed remains were recovered (Mays 1998). Low relative numbers of these bones is often cited as evidence for prior burial or sub-aerial exposure of remains (Mays 1998; Carr & Knüsel 1997). This method is compromised by the fact that the same small bones are also more vulnerable to other taphonomic interventions, such as chemical degradation, transportation away from the body and excavation bias (Gordon & Buikstra 1981; Mays 1998).

Signs of fracture, weathering and carnivore alteration on bone samples have been used to infer excarnation by sub-aerial exposure (Carr & Knüsel 1997; Craig *et al.* 2005; Leach 2006; Smith 2006; Redfern 1998). However, this model would not apply had sub-aerially exposed remains been protected from alteration by a barrier or use of an elevated platform (Madgwick 2008; Redfern 2008). The presence of significant bone weathering would be dependent on how long the bare bones had been exposed to the elements before they were collected. It might be expected that tool marks would be found upon the bones of a dismembered or defleshed individual, but the presence of such marks would be dependent on the skill of the butcher and the objective of processing (Guilday 1962; Binford 1981; Fisher 1995). All of these techniques would expose the bone to different levels of putrefactive action and bacterial bone bioerosion. Therefore, measurement of bone bioerosion would provide a more certain method for determining the funerary treatment that produced disarticulated assemblages.

Measurements of bacterial bone bioerosion may also be useful in discerning hidden taphonomic processes. For instance, the limited pattern of bacterial bioerosion observed within the skeletons excavated from Cladh Hallan suggested that these individuals had experienced limited putrefaction (Parker Pearson *et al.* 2005; 2007). This observation was combined with the results of dating, isotopic, taphonomic, osteological and ancient DNA evidence to suggest that these skeletons had been constructed out of the mummified parts of

several individuals (Parker Pearson *et al.* 2005; 2007; Hanna *et al.* 2012) (Image 2.23). These findings raised questions regarding how mummification can be identified in the British archaeological record, given that the wet environment will eventually cause the preserved soft tissues to disintegrate (Parker Pearson *et al.* 2005). The case for mummification at Cladh Hallan consisted of specific dating, osteological and taphonomic evidence that is unlikely to be replicated at every archaeological site where mummification was practised (Parker Pearson *et al.* 2005; 2007). However, the neutralisation of putrefactive gut bacteria associated with most mechanisms of mummification would ensure that the bones from these categories of remains would have been subjected to low levels of bacterial bone bioerosion (Weinstein *et al.* 1981; Thompson & Cowen 1984; Brothwell & Bourke 1995; Hess *et al.* 1998; Aufderheide 2003; Lynnerup 2007). Moreover, this limited pattern of bioerosion should stand in contrast to that observed within other articulated skeletons that were buried soon after death (Jans *et al.* 2004; Nielsen-Marsh *et al.* 2007). Measures of bone bioerosion might constitute the only method of identifying prior practices of evisceration and mummification in the past.

Image 2.23: Photograph of the adult male body that was recovered from the Bronze Age settlement site of Cladh Hallan, South Uist. A suite of analytical techniques suggested that this body had been composed out of the mummified parts of several individuals (image courtesy of Mike Parker Pearson).

2.4 RESEARCH DESIGN

The primary objective of the present study is to determine and characterise the nature of any relationship between bone diagenesis and funerary treatment and assess whether any

association is accurate and strong enough for microscopic analysis of archaeological remains to be used effectively in reconstructions of funerary treatment. These objectives can be summed up in the following research questions:

1. Is there a relationship between funerary treatment and bone diagenesis that is strong enough to be detected by microscopic analysis of archaeological bone?

2. Does the relationship between bone diagenesis and funerary treatment conform to predictive models of diagenesis inferred by studies of cadaveric decomposition?

3. Is the strength and nature of the relationship between bone diagenesis and funerary rite such that certain treatments can be said to produce characteristic patterns of diagenesis that can be recognised through the microscopic analysis of archaeological bone microstructure?

4. How can measures of bone diagenesis, particularly the microscopic assessment of archaeological bones, be usefully employed in reconstructions of funerary processes?

The past studies of the causes of bone diagenesis have utilised one of three different types of experiment approaches:

1. Microstructural analysis of bone sampled from a small number of experimentally-deposited carcasses.
2. Microstructural analysis of bone sampled from a small number of forensic cadavers recovered from variable environments.
3. Microstructural analysis of large samples of archaeological bone from variable periods and sites.

The first two approaches would have allowed for the observation of the development of bone diagenesis within remains that had been variably deposited in known ways under controlled conditions (Yoshino *et al.* 1991; Bell *et al.* 1996; Nicholson 1996; Fernández-Jalvo *et al.* 2010; White 2009; Turner-Walker 2012). Such experimental approaches would allow for the direct observation of relationships between measures of bone diagenesis and funerary treatment. However, neither of these methodologies could be utilised for the current study for ethical,

legal and practical reasons. The University of Sheffield Department of Archaeology does not hold a licence under the Human Tissue Act (2004) to retain human remains less than one hundred years old. The use of human cadavers for forensic experimentation is not authorised within the U.K. and would not be considered ethical based on the University of Sheffield's standards.

The use of non-human analogues in taphonomic experiments would mostly neutralise the ethical and legal problems, as long as animals were not euthanized especially for use in the study. However, a three-year PhD project does not provide sufficient time to conduct a real-time study of cadaveric decomposition (Rodriguez & Bass 1983; 1985; Bass 1997). The University of Sheffield Department of Archaeology holds a substantial collection of archaeological remains that would have experienced a full diagenetic cycle related to their death and deposition. Microscopic investigation of archaeological remains provided the most practical scenario for determining the interaction between bone diagenesis and funerary rites.

Past studies of the relationship between diagenesis and taphonomy in archaeological bone have focussed on the differences between articulated human and butchered faunal material (Jans *et al.* 2004; Nielsen-Marsh *et al.* 2007). It was possible that the relationship between bone diagenesis and early *post mortem* treatment could be investigated through further comparisons of archaeological bones from different species that were likely to have experienced separate taphonomic trajectories. However, such an experimental model would be compromised by the intrinsic differences between species as well as diversity in the nature of past treatment of categories of remains.

Gut microbiome and microstructural organisation of bone differ between species (Nicholson 1997; Martiniakova *et al.* 2006; Hillier & Bell 2007; Crescimanno & Stout 2012; Dominguez & Crowder 2012). Bone from domesticated species that are most often recovered from archaeological sites may have been subject to a complex combination of anthropogenic treatments relating to carcass processing, cooking and disposal (Mulville *et al.* 2011). Bones from wild species do not present an attractive source for comparison, as their bodies also may have been subjected to a variety of uncontrolled taphonomic processes that may have affected bone diagenesis, including sub-aerial exposure, scavenging and partial burial.

It has been suggested that the skeletons of domesticated animals that were not often consumed at European archaeological sites, such as dogs, would provide the best comparisons to human material, although problems would still arise relating to the intrinsic differences between species (Parker Pearson *et al.* 2005; Mulville *et al.* 2011). Any experimental design

that compared diagenesis within archaeological bones of different species would be undermined by questions regarding the validity of comparisons (Turner-Walker 2008).

It was necessary to focus work for the current study on archaeological bone from a single species. The emphasis on funerary treatment meant that the best option was to concentrate on variations in diagenesis within archaeological human bone assemblages. Human remains from past and present societies have often been subjected to a large variety of anthropogenic and natural taphonomic processes (Parker Pearson *et al.* 1999). However, the significance afforded to human remains by most past populations has meant that their exposure to complex random biostratinomic processes has usually been controlled or limited (Parker Pearson *et al.* 1999). Therefore it is likely that an archaeological human bone will have experienced fewer and less variable taphonomic events than most faunal bones from the same sites. The exclusive use of human remains would ensure a level of consistency that would improve upon previous studies of diagenesis in archaeological bones (Bell *et al.* 1996; Nielsen-Marsh & Hedges 2000; Jans *et al.* 2004).

The difficulty in narrowing the scope of the current study to human bone was in locating assemblages that had been treated in known but variable ways. A crude idea of the relationship between diagenesis and funerary ritual could be attained through comparison of separate human bone assemblages that were known to have been treated divergently. It would not matter if the specific method was unknown, as long as there was evidence that the treatment of the bodies differed in a way that would probably have affected the bone exposure to putrefaction.

The main work for this project was to be undertaken at the University of Sheffield and facilities around the U.K. It was deemed practical to identify British archaeological periods that provide human bone assemblages that could address the research questions of the current project. Documentation of burial rites began and continued intermittently through the Historical (A.D. 34 – present day) periods of Britain, during which time the majority of the dead were invariably buried intact immediately after death. Immediate inhumation during these periods is predominantly related to Christian religious rites, although the same process was also utilised in Roman Britain from the 2nd century A.D. and the pagan Early Anglo-Saxon era (5th-7th century A.D.) (Toynbee 1996; Lucy 2000). The Historical archaeological record of Britain provides a swathe of time where the majority of the dead that were not cremated were consistently afforded a known form of funerary treatment. This consistency in funerary treatment is confirmed by the anatomical articulation of the majority of human skeletons

recovered from sites dating to these periods. If a body is not buried soon after death, bodily decomposition would ensure that there would be some skeletal disarticulation (Roksandic 2002; Duday 2006).

An assemblage of British Historical human bone could be used to test whether consistent treatment produces consistent signatures of bacterial bone bioerosion. If funerary treatment has a primary role in dictating bacterial bone bioerosion, human bone excavated from British Historical contexts should demonstrate consistent patterns of internal bacterial attack, regardless of environment, temporal phase or other potentially influential factors. The conclusions of experimental studies of cadaveric decomposition can be used to predict how different depositional circumstances would have affected the level of putrefaction a bone experienced. Burial in aerobic environments allows unabated microbial decomposition and exposes the bones of a body to the maximum levels of putrefactive bacterial attack (Rodriguez & Bass 1985; Mant 1987; Manhein 1997; Rodriguez 1997; Campobasso *et al.* 2001; Fielder & Graw 2003; Wilson *et al.* 2007; Vass 2011). If bacterial bone bioerosion is linked to putrefaction and funerary treatment it would be expected that bones of individuals who were inhumed soon after death would consistently demonstrate the highest levels of bacterial attack (Nielsen-Marsh & Hedges 2000; Jans *et al.* 2004). Extensive levels of bacterial bone bioerosion promoted by immediate inhumation could provide a baseline against which all other diagenetic signatures could be compared to discern likely *post mortem* treatment.

The relationship between bacterial bioerosion and funerary treatment could be tested by comparing the results from the Historical samples against another human bone assemblage from a similar environment that was known to have been treated more variably. Skeletal disarticulation suggests that an individual had been subjected to early *post mortem* treatment that either did not involve immediate inhumation, or of which immediate inhumation formed only one part. Most British disarticulated archaeological human bone assemblages that were likely to have been disassembled by primary mortuary treatment, rather than subsequent disturbance, originate from Later Prehistoric periods; from the Neolithic to the end of the pre-Roman Iron Age (c.4000 B.C.-A.D. 43). There is no surviving primary documentation from these periods and no certainty regarding the types of funerary rites that were practised (Parker Pearson 1999; Darvill 2010). However, there is archaeological evidence that a variety of different funerary rites were practised in Later Prehistoric Britain, including inhumation, primary burial, dismemberment, defleshing, excarnation and mummification (Parker Pearson 1999; Wysocki & Whittle 2000; Parker Pearson *et al.* 2005; Brück 2006; Smith 2006; Redfern 2008; Darvill 2010).

Any funerary treatment that did not involve the body decomposing entirely within the ground is likely to drag the signature of bacterial bioerosion away from the baseline inhumation level. This notion is substantiated by forensic and experimental studies, which have suggested that spontaneous endogenous decomposition of unburied remains is swiftly supplanted by exogenous factors (Rodriguez & Bass 1983; 1985; Galloway *et al.* 1989; Dent *et al.* 2004; Wilson *et al.* 2007; Campobasso *et al.* 2011; Vass 2011).The exact method of treatment afforded to individuals represented within an assemblage does not need to be known for it to provide a viable comparison to the Historical remains, there only needs to be evidence for the practise of funerary processes that would have affected putrefaction in a way that deviated from inhumation. A relationship between funerary process and putrefactive bone bioerosion would dictate that human remains sampled from Later Prehistoric British contexts should demonstrate variably lower levels of bacterial attack compared with the Historical human bone assemblage. Comparison of bacterial bioerosion within human remains from Historical and Later Prehistoric British sites would provide a rudimentary but effective scrutiny of the relationship between funerary treatment and bacterial bioerosion by testing a simple dichotomy of variable and consistent treatment. The nature of any variation between these two assemblages would be informative regarding whether studies of cadaveric decomposition can be used to predict levels of bacterial bioerosion encouraged by particular forms of *post mortem* treatment.

This comparison of these two assemblages may be problematic in addressing the research questions because of equifinality. Bones excavated from Later Prehistoric sites show superficial signs of having had been treated differently from their Historical counterparts, particularly in terms of their anatomical articulation. However it is possible that the *post mortem* treatment of these bones exposed them to similar levels of putrefaction as immediate burial. For instance, if the skeletal disarticulation of the Later Prehistoric skeletons had been caused by primary burial, then their bones would have experienced the same levels of putrefaction as those from inhumed Historical individuals. This outcome would produce a false negative regarding the relationship between funerary treatment and bacterial bone bioerosion.

The problem of equifinality could not be avoided. Negative results regarding the expected differences between the Later Prehistoric and Historical human bone could occur as a result of there being no relationship between bacterial bioerosion and funerary treatment or that bodies had all subject to similar treatments that were subsequently obfuscated by secondary manipulation. Such a result would not undermine the aims of this project entirely, as the results from the consistently-treated Historical remains would still go some way towards

assessing the relationship between bacterial bone bioerosion, putrefaction and funerary treatment. However, a negative result regarding the expected differences in bacterial bone bioerosion between Later Prehistoric and Historical skeletal assemblages would limit the conclusions of the current study to the effects of immediate burial.

A specific set of hypotheses were formulated regarding the relationship between funerary treatment and bacterial bioerosion:

1. If bacterial bone bioerosion is linked to funerary processes, bones recovered from Historical cemeteries will demonstrate consistent patterns of internal bacterial bioerosion.

2. If the nature of bacterial bone bioerosion is controlled by the extent to which early funerary processes dictate bodily putrefaction, all bones from Historical cemeteries will be characterised by high levels of internal bacterial attack.

3. If bacterial bone bioerosion can be used to distinguish between funerary rites, there will be a significant difference between the histological signatures of bone from Later Prehistoric and Historical periods.

It was assumed that only burial could be responsible for the survival of an articulated skeleton into the archaeological record. Bone from both Historical and Later Prehistoric articulated skeletons would be expected to demonstrate analogous levels of bacterial bone bioerosion. There was an expectation that most of the variation in bacterial bone bioerosion observed amongst the Later Prehistoric remains would originate within the disarticulated/partially articulated assemblage. Positive results regarding these hypotheses would indicate that factors relating to early *post mortem* treatment have a dominant role in dictating bacterial bone bioerosion, negating the effect of other potential influences. It would be unlikely that these hypotheses would be confirmed if bacterial bone bioerosion was primarily controlled by factors other than funerary treatment.

No assumptions were made regarding specific treatments of individual Later Prehistoric skeletons, only that the evidence for their variable treatment meant that levels of bacterial attack were expected to be diverse. Substantiation of the hypotheses would suggest that

results from forensic and experimental studies of decomposition could be used to make inferences about the treatments responsible for certain patterns of bacterial bone bioerosion and attempts could be made to interpret the likely funerary treatments responsible for the individual and site-specific signatures of bacterial bioerosion amongst the Later Prehistoric assemblage. This process would allow the production of exemplary reports that demonstrated how measures of bone diagenesis may be used in inferring funerary treatment.

The research questions were framed with reference to bone diagenesis, rather than bacterial bioerosion exclusively. The current project is concerned with recording variation in overall bone diagenesis with funerary treatment, not just bacterial bioerosion. Certain diagenetic changes to bone may directly affect bacterial bioerosion or reflect processes and environments that would have interfered with putrefaction (Nielsen-Marsh *et al*. 2000; Jans *et al*. 2004; Turner-Walker & Jans 2008; Hollund *et al.* 2012). For instance, certain types of discolouration within bone microstructure have been linked to anoxic decompositional environments (Turner-Walker & Jans 20008; Hollund *et al.* 2012). Bacterial bioerosion has to be understood within its diagenetic context if any correlations between bacterial bioerosion and funerary treatment are to be substantiated.

There is evidence that other types of bone diagenesis may be linked with early *post mortem* treatment. For instance, fungal Wedl tunnelling appears more often within butchered bones (Jans *et al*. 2004). It was not possible to predict the relationships between funerary treatment and forms of bone diagenesis such as mineral dissolution, Wedl bioerosion or visual diagenetic changes. The use of Later Prehistoric/Historical dichotomy as a proxy for funerary treatment would mean that associations between funerary treatment and non-bacterial forms of diagenesis would have to be assessed through an investigation of how each of these factors varied with archaeological phase as well as other recorded variables. Measures of non-bacterial diagenetic changes included in the current study were used to supplement the results from the gauges of bacterial bioerosion in addressing the research questions.

3 METHODOLOGY

This chapter provides an outline of the methods and techniques that were used to address the research questions outlined in the previous chapter. The first section provides a brief discussion of how remains from particular assemblages were chosen. The sampling strategy had to be adaptive to each site, and therefore most of the discussion of sampling was included within the Materials chapter. However it was still pertinent to include a small section on sampling within this Methodology to explain the main objectives. The sampling section is followed by a justification for the techniques that were applied to the archaeological remains, which is followed by a description of methods of preparation and analysis. This section is followed by a description of the systems that were used to quantify diagenetic change using these analytical methods. A number of variables that were considered to have potentially influenced bone diagenesis were also recorded to assess their effect on diagenetic parameters. The variables that were chosen and the manner in which they were recorded are discussed in the penultimate section. The final part of this chapter explains the statistical tests that were used in the current study. This section includes an explanation of how statistical testing was used to address the research questions posed, particularly with regards to the hypotheses relating to bacterial bone bioerosion.

3.1 SAMPLING

3.1.1 Sampling Strategy

The success of the current study was dependent upon the analysis of a large number of samples to record trends in diagenesis within bone samples from dispersed sites. The University of Sheffield Department of Archaeology held a large collection of ready-made human bone thin sections from Historical and Later Prehistoric sites that could be analysed histologically using transmitted light microscopy. These samples had been produced for earlier undergraduate and postgraduate research projects. These projects had usually studied human remains from single sites. Diagenetic change within majority of samples had been analysed and interpreted using various means, but the results had never been standardised, collated and

examined as a whole. The sampling strategy for each separate project was not always guided by research aims analogous to those of the current study. However, the number of ready-made samples that were available meant that their potential contribution towards the fulfilment of the current project's research aims outweighed any problems relating to sampling. Moreover, this collection included bone thin sections from material that was no longer held at the University of Sheffield, allowing access to assemblages that were no longer directly available.

The varied research questions the premade samples were originally used to address would help to cancel any biases when the whole population was examined as a whole. The predictions regarding bacterial bioerosion should not have been affected by any biases in the sampling of remains from these sites, as the underlying principles should apply to all archaeological remains. Attempts to control for potentially influential variables would help to counteract biases in sampling. Therefore, some of the sample sets included in the current study did not represent the ideal assemblages from particular sites, but were still valid. The rationale behind the choice of samples from each site is provided within the Materials chapter.

The majority of thin sections were assessed without any prior knowledge of previous studies in order to ensure that their conclusions did not unconsciously influence their assessment for the current project. Inevitably, previous interaction with some of the samples in the collection meant that the author had prior knowledge of levels of diagenesis in some instances. It was considered whether it was appropriate to include samples whose histological preservation was previously known by the author. It was possible that the inclusion of these remains may have introduced unconscious bias. However, the author sampled and assessed these remains originally without any prior knowledge of their microscopic preservation. The inclusion of these remains within the current study was not selective; they happened to make up part of the University of Sheffield's thin sections, the entirety of which were included in the present study. Those samples that had been examined previously by the author only constituted a small proportion of the overall study sample and should not have introduced any significant biases.

The inclusions of samples from previous studies as well as the variation in the sites that were included in the current study meant that sampling strategy varied adaptively from site to site. Where possible, sampling of Historical material was based upon obtaining a random sample of remains that represented the full extent of a site. The sampling of Later Prehistoric remains attempted to maximise sample size whilst obtaining specimens that represented the full

spectrum of funerary treatments. Variation in funerary treatment was recognised by variable stages of skeletal articulation as well as evidence for *post mortem* manipulation such as cut marks.

3.1.2 Skeletal Element

Many of the previous archaeological, experimental and forensic studies of bone diagenesis did not consistently use samples from the same skeletal element, even when the bone originated from the same species (Bell *et al.* 1996; Nicholson 1996; Davis 1997; Jans *et al.* 2004; Turner-Walker & Jans 2008; Fernández-Jalvo *et al.* 2010). Some researchers have attempted to control for potential differences in diagenesis of skeletal elements by focussing sampling on the femur, although all resorted to using samples from other skeletal elements, particularly other long bones (Nielsen-Marsh & Hedges 2000: Jans *et al.* 2004; Hollund *et al.* 2012).

Proportions of secondary osteonal bone vary with skeletal element, as bones from different parts of the body are not remodelled similarly over an individual's lifetime (Junqueira *et al.* 1986). The relationship between bioerosion and natural bone porosities suggests that it is probable that the nature and extent of bacterial attack will vary with skeletal element. Jans *et al.* (2004) found that bones in closest proximity to the internal organs, such as the ribs and lumbar vertebrae, suffered higher levels of bacterial attack (Jans *et al.* 2004). Hanson & Buikstra (1987) also noted that rib samples tended to have been more severely bioeroded than any other skeletal element. Jans *et al.* (2004: 91) attributed this patterning to the closer proximity of these bones to the abdominal putrefactive bacteria. This interpretation is questionable under an endogenous model of bioerosion, as gut bacteria migrate around the body within a few hours after death, which would provide ample opportunity for microbiota to access all parts of a skeleton over the duration of bodily decomposition (Polson *et al.* 1985; Child 1995a; Bell *et al.* 1996). However, bacteria require a liquid medium for transmigration and it is possible that *post mortem* coagulation of the blood might impede their progression to peripheral anatomical areas.

Other studies of diagenesis in varied skeletal elements infrequently mention differences in diagenesis between particular bones (Nicholson 1996; Nielsen-Marsh *et al.* 2000). It is difficult to ascertain whether the lack of discussion was due to there being no observable difference in diagenesis between skeletal elements or because this relationship was not tested (Nicholson 1996; Nielsen-Marsh *et al.* 2000). Differential diagenesis of skeletal elements may be related to

ratios of trabecular and cortical bone. The large marrow-containing cavities found within trabecular bone expose more of the internal surface area to bacterial attack or interaction with the external environment. The large trabecular cavities reduces bone volume per unit of space (Turner-Walker 2008). Attacking microbes or chemical processes would require less time to degrade trabecular bone. Ribs and vertebrae predominantly consist of trabecular bone and so Hanson & Buikstra's (1987) and Jans *et al.*'s (2004) results could have reflected different constitutions of discrete skeletal elements rather than their anatomical position.

The lack of clarity regarding variation in diagenesis across human skeletons made it necessary to control the skeletal element that was sampled from each individual included in the current study. The ideal situation was that all samples originated from the same skeletal element. Bones that demonstrate high proportions of cortical bone are the best candidates for histological analysis, as the high porosity of trabecular bone renders sample preparation more difficult and ensures that there is less microstructure visible in each section. Long bones are usually chosen for histological analysis due to their high proportions of cortical bone, robusticity and survival rate (Nielsen-Marsh & Hedges 2000; Jans *et al.* 2004). The femur is the most common choice of long bone for diagenetic studies, on the basis that it is the closest long bong to the gut and is possibly most sensitive to enteric microbial activity (Nielsen-Marsh *et al.* 2000; Jans *et al.* 2004; Hollund *et al.* 2012). Sampling for the present study preferentially targeted femora to ensure consistency and maximise comparability with other studies of bone diagenesis.

There was no theoretical or evidential reason to suggest that bone bioerosion or bone diagenesis generally would vary significantly between skeletal antimeres, as long as all parts of a body had decomposed under similar environmental conditions (Jans *et al.* 2004). However, it was decided for consistency that the default position would be to sample the left femur where possible. The right femur was sampled in situations where the left was not available or where the sampling of the right femur would have caused less damage to the research potential of a skeleton, for instance, in cases where the right femur was significantly more fragmented than the left.

Historical remains were likely to have been excavated in anatomical articulation within discrete grave cuts, and bones from these examples could be confidently assigned to a specific individual. However, many of the Later Prehistoric bones originated from assemblages of comingled disarticulated remains. The Historical assemblage included disarticulated material that had been collected as part of charnel deposits, or that had accrued within grave fills as a

result of disinterment by grave digging. Anatomical sidings of samples become important in these instances in ensuring that skeletal elements from the same individual were not sampled more than once. The femur that was chosen in each case was dependent upon availability. The default position was to sample from the left femur consistently to ensure no replicate sampling of individuals. Right femora were sampled at sites where this element was more abundant and its selection facilitated larger sample sizes.

Femoral samples were easily obtainable from the disarticulated and articulated Historical assemblages where there were high numbers of individuals represented and abundant desirable skeletal elements. However, the volume of human bone recovered from the Later Prehistoric contexts was sometimes too low to acquire a good sample size from femora alone. In these rare situations, samples were taken from alternative skeletal elements. The rationale behind the choice of samples in these cases was specific to each site. The two main variables that had to be controlled in selecting these samples were proportions of cortical and trabecular bone and proximity of a skeletal element to the gut. A system of selection was established based upon structural and anatomical similarity to the femur. Shafts of long bones contain relatively analogous proportions of cortical and trabecular bone (Junqueira *et al.* 1985). If a femur was not available from a discrete individual, than the next preferred choice was a different long bone from the lower limb, then humerii, then any upper limb long bone, then any available long bone (including clavicles or metatarsals/metacarpals). This system was expected to limit variation in diagenesis that might have occurred as a result of variability in the diagenetic potential of discrete skeletal elements.

The majority of ready-made samples available within the University of Sheffield's collection consisted of long bones from discrete individuals. Most of these samples were femoral and could be included within the current study without any difficulty. The collection also contained small numbers of tibiae, humerii and fibulae from discrete individuals. The success of the current study was dependent upon optimising sample size. Therefore, it was prudent to include thin sections from non-femoral long bones, particularly in examples where their exclusion would have significantly reduced site sample sizes.

The potential influence of bone architecture on diagenesis meant that it was necessary to consistently target sampling of long bones at the diaphyses (Hedges *et al.* 1995; Turner-Walker 2008). Long bone diaphyses were sampled in all cases, as they are mostly constituted of cortical bone, as opposed to the epiphyses, which include higher proportions of trabeculae. Inevitably there was some variation in exact diaphyseal location that was sampled, particularly

in cases where bones were fragmented or incomplete. All samples were taken from variable locations on the long bone mid-shaft.

Attempts were made to account for the potential element-specific patterns of bone diagenesis at the analysis stage. The histological preservation of non-femoral skeletal elements was scrutinised to establish whether certain bones were intrinsically more or less susceptible to diagenetic processes and whether variation related to proportions of cortical bone, proximity to the gut, or any other factor. Significant results were controlled in the overall analysis. Any skeletal elements that consistently deviated from the diagenetic norm were excluded from the analysis.

3.2 Analysis of Bone Diagenesis

3.2.1 Thin Section Light Microscopy

The University of Sheffield Department of Archaeology included the facilities to conduct histological analysis of bone samples using thin section transmitted light microscopy. This technique allows for the observation of the histological preservation of bone as well as any staining, inclusions and infiltrations (Hackett 1981; Garland 1987; Schultz 1997). The images that this technique produces do not have the same level of resolution as SEM (Turner-Walker & Syversen 2002; Hollund *et al.* 2012). In particular the small pits and microchannels that constitute MFD can be visualised with much greater clarity using SEM (Turner-Walker *et al.* 2002).

SEM was not available within the University of Sheffield Department of Archaeology and access to use relevant facilities would have been time-consuming and expensive. It was unlikely that use of SEM would have facilitated the analysis of large numbers of samples. The resolution of analysis provided by thin section light microscopy was good enough to address the aims of the current study.

The facilities available at the University of Sheffield meant that the methods of sample preparation and analysis involved with thin section light microscopy were quick and facilitated the preparation of large numbers of samples. Assessment of histological preservation using SEM and thin section light microscopy both utilise scales that translate the percentage of remaining bone microstructure into an ordinal score (Hedges *et al.* 1995; Turner-Walker &

Syversen 2002). Therefore the basic quantified assessments of histological preservation by either thin section light microscopy or SEM were unlikely to differ substantially. All of the ready-made samples available within The University of Sheffield Department of Archaeology's collections consisted of thin sections prepared for light microscopy. The use of thin sections analysis would allow the incorporation of this substantial collection. The practicalities and availability of the thin section light microscopy in meant that this technique was the obvious choice for use in the analysis and assessment of histological preservation in bone samples for the current study.

3.2.2 Analysis of the Mineral Phase

Thin section light microscopy cannot be used to accurately record diagenesis to the bone mineral. The aim of the current study was to attempt to characterise whole bone diagenesis. None of the techniques for measuring bone crystallinity were available at the University of Sheffield Department of Archaeology. The only way that the bone mineral could be analysed was through application to outside institutions. The requirement to access outside institutions for crystallinity analyses meant that it was unlikely that every bone sample included could be subjected to such testing. It was hoped that analysing the crystallinity of two or three specimens from each site would provide some indication as to the specific changes that had occurred throughout site assemblages. Time would be allocated for any additional sampling of bones that had provided anomalous readings. For instance, in situations where the alteration to the bone mineral did not correspond with the burial conditions. Such a result could indicate that the depositional environment of a skeleton had changed (Parker Pearson *et al.* 2005).

X-ray diffraction techniques could be accessed through application to the Diamond Light Source synchrotron facility in Didcot, Oxfordshire. The Diamond Light Source puts out invitations to use particular beams in research projects in April and September. If accepted, the researcher is provided with a block of days when they can utilise their chosen light source. Applications for beamtime were sent to the Diamond Light facility in September 2010, April 2011 and September 2011 and April 2012. Unfortunately, none of these applications were successful. The failure to gain access to techniques was disappointing, but did not affect the ability of the current project to address the primary research aims. Measures of bone mineral change are mostly pertinent to environmental degradation or heat treatment. The main focus of the current project was the assessment of bacterial bioerosion which could be gauged using

the available techniques. The lack of a holistic diagenetic characterisation of the bone samples narrowed the project from a study of overall diagenesis to one that mostly related to bioerosion and histological preservation.

3.3 HUMAN BONE THIN SECTION PREPARATION & ANALYSIS

3.3.1 Sampling Bone for Thin Sectioning

The saw microtome method of producing thin sections that was employed in the current study relies on an initial trimming slice to zero the level of the sample and allow for the section thickness to be measured out using the built-in micrometer. The clamp that holds the sample only drops around six centimetres into the central waste water well (Image 3.1). Bone samples longer than six centimetres protrude over the blade. In these cases, it was easier to cut a separate sample from the whole bone or bone fragment. The clamp has a maximum diameter of around four centimetres, and so wider bone fragments also had to be cut to fit. Smaller samples had to be taken from complete femora in order to provide a specimen that could be installed within the saw microtome. The need to acquire bone samples below certain dimensions necessitated the preferential sampling of fragmented remains, as sampling directly from a bone fragment had a lower impact on research potential than cutting a piece from an intact skeletal element.

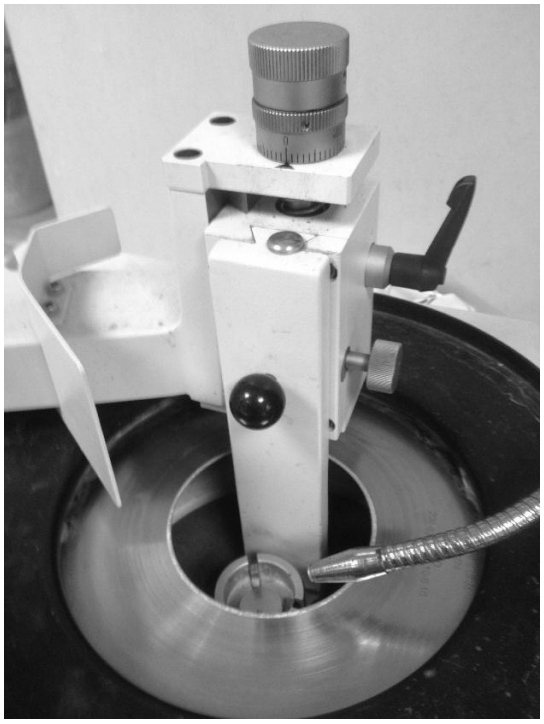

Image 3.1: Close-up photograph of the sample clamp in situ within the saw microtome. The clamp can only drop so far into the waste water well (taken by the author).

In situations where it was necessary to cut a sample from a bone, no more than what was considered essential for the production of a useful thin section was extracted. Samples usually consisted of a section of bone around one centimetre by one centimetre that encompassed the entire cortical cross section of the long bone shaft down to the medullary cavity (Image 3.2). Sections were removed from the bone using a Foredom K.1070 rotary saw. The use of bone fragments meant that the overall cross-sectional area represented by each bone thin section varied. However variation in cross-sectional area should not have affected the scope of analysis, as the method of assessment measures the proportion of bone affected by bacterial attack, which does not differ significantly across different parts of the long bone cross section (Hackett 1981; Hedges *et al.* 1995).

Image 3.2: Archaeological human femur that had been sampled for thin section analysis. The sample of bone that has been taken is typical the size of fragment required for cutting in the saw microtome (taken by the author).

Thin sections of bone can be transverse, *i.e.* perpendicular to the long axis of the bone, or longitudinal, *i.e.* in parallel with the long axis of the bone. The majority of studies that have investigated and characterised osteolytic microbial alteration and bone microstructure have examined transverse thin sections (Stout 1978; Hackett 1981; Garland 1987; Schultz 1997). Anatomical features and diagenetic changes are easier to identify and characterise within transverse sections of bone (Stout 1978; Hackett 1981; Garland 1987; Schultz 1997). Transverse thin sections can also cover the whole cross-sectional area of a bone and provide a better indication of overall diagenesis. Most of the material included in the University of Sheffield's collections consisted of transverse thin sections. Only transverse sections of bone were produced and included in the current study.

3.3.2 Preparation of Human Bone Thin Sections

Bone thin sections can be prepared in one of two different ways. A thick section can be cut from a bone sample using a regular vertical microtome and grinded down to the required thickness using abrasives (de Boer *et al.* 2013). Bone thin sections can also be produced directly using a saw microtome. Saw microtomes consist of horizontal circular blade mounted onto a micrometer that allows the precise production of bone sections a few microns in thickness. Early blade microtomes were prone to damaging archaeological samples. Thin

sections produced using this method often demonstrated microfissures as a result of the stress produced by the blade microtome (Schultz 2001). Annular saw microtomes were designed specifically for cutting hard materials such as bone and teeth. Saw microtomes include diamond-tipped blades that are much less prone to damaging fresh and archaeological bone samples during cutting.

Production of thin sections using a saw microtome is less laborious than a grinding method. Grinding requires consolidation of the bone structure by an embedding agent, which voids the research potential of left-over fragments. Archaeological bone specimens rarely have to be reinforced using an embedding agent for thin section production using an annular microtome. Fragments of bone left over from archaeological samples cut using a saw microtome maintain their potential for use in future analyses. The grinding method involves larger portions of bone being ground down to produce a single thin section. The use of an annular microtome allows for the production of several thin sections from a bone fragment of equivalent size and most of the original sample is left over at the end. Once the trimming slice has been removed, a bone fragment will only lose a few hundred microns of its length to the thin-sectioning process. All of the thin sections that constituted the Department of Archaeology's collections consisted of samples that had been produced by a saw microtome. Thin sections were prepared using the saw microtome for the current project, as this method represented a quick, cheap and efficient option and would allow sections to be produced consistent with those that were already accessible.

All of the thin sections used in the current study were cut from the bone samples using a Leica 1600 diamond-saw microtome. This machine can produce bone thin sections between five and two hundred microns in thickness with a precision of five microns. The blade of the microtome is cooled during the cutting process by water from the mains. The movement of the microtome clamp holding the sample towards the saw blade is controlled by an internal spring. A knob on the side of the machine manipulates this spring and controls the cutting speed. The optimal cutting speed varied between samples. If a section was cut too quickly, remnants of the progress of the saw were embedded within the bone surface, which spoiled the quality of the section. Slow cutting ensured a good quality section. However, a slow cut was not always suited to the condition of the archaeological samples, which sometimes crumbled away with the progress of the blade.

The thickness to which each thin section was cut was dependent upon the integrity of the bone samples. Well-preserved samples could be cut to thicknesses of 50 microns or lower,

whereas more friable specimens would not maintain their integrity at thicknesses below 120 microns. The thickness of a bone section affects the appearance of the microstructures. Thicker sections are more opaque and microstructural features can appear altered when compared to the same structures in thinner sections. Microbial tunnelling within thicker sections has an amorphous appearance due to the superimposition of several layers of activity. The difference in thickness between the sections used in the current study should not have significantly affected the ability to identify and characterise features of interest. However, differences in thickness were recorded and considered during examination of thin sections.

The need to cool the blade through the application of water from the mains meant that the thin sections produced by the microtome were wet when they were retrieved from the machine. Each thin section was left to dry naturally before being mounted. It was possible that elements or microorganisms within the water, as well as the movement of water itself, may have affected the histological preservation of each section. No diagenetic phenomena were observed within any of the thin sections post mounting. The histological preservation of some of the samples that were included in the current study was immaculate. Thin sections of fresh animal bone that had been prepared using a similar method showed no detrimental effects to their microstructures as a result of the thin sectioning process. The time that the bone was exposed to water and the relative rapidity of sample drying ensured that the histological integrity of the bone thin sections was not significantly affected by the cutting method.

Several sections were taken from each bone sample at different thicknesses and different speeds to ensure that a good quality section was obtained. Acceptable sections were produced from the majority of bone samples at between 50 and 100 microns in thickness. A small number of friable samples had to be cut at thicknesses between 100 and 120 microns. Any samples that continually failed to maintain their integrity at 120 microns were embedded in resin to consolidate their structure. This thickness was chosen because thin sections cut above this threshold might have begun to demonstrate increased levels of opacity that could have been detrimental to the assessment of the bone microstructure (de Boer *et al.* 2013). Studies of bone thin sections often involve the decalcification or staining of samples to enhance microstructural features (de Boer *et al.* 2013). These methods were not necessary for the histological examination of the samples used in the present study.

Thin sections were mounted onto glass microscope slides using a few drops of Entellan microscopy resin (Merck chemicals) and a glass coverslip. The glass coverslip was placed onto the fluid at each corner sequentially to minimise formation of air bubbles that might obscure

microstructural features. Entellan consists of a number of synthetic polymers suspended in xylene. This type of resin was chosen for mounting as its refractive index is similar to glass, it cures rapidly (20 minutes at room temperature), does not require any prior preparation, does not degrade or change colour significantly over time, is resistant to temperature and light and is pH neutral. The use of this mounting fluid ensured that good quality and durable bone thin sections could be produced rapidly. Pure xylene was used to clean up any excess fluid or spillages. Entellan can produce toxic fumes, therefore all thin sections were mounted under the hood of a fume cupboard.

The thin sections already held within the Department of Archaeology's collections had been prepared in a similar manner, although some had been mounted using the Euparal (Alpha Chemika) microscopy fluid. This mounting medium has similar properties to Entellan in terms of durability and inertness. However, Euparal has a slight yellowish tint. The weakness of this yellow tint meant that the use of this fluid would not have affected histomorphological assessments of bone thin sections.

After mounting, each thin section was left to cure for a few hours. The Entellan should have cured within twenty minutes, but more time was allocated to make sure the mounting medium was not disturbed during drying. After the sections were dried, each individual slide was permanently labelled with the site details, context numbers, specimen numbers, slide number and section thickness.

3.3.3 Embedding

Bone samples that were too fragile to cut at 120 microns were embedded within the epoxy resin Araldite 2020 (Huntsman Advanced Materials). Resins of this sort do not consolidate the bone structure through impregnation, but surround the bone supportively so that it does not crumble when cut by the microtome. Araldite was chosen because it is inert and has a refractive index similar to glass. Araldite cures quickly compared to other embedding mediums, and whilst prior heating decreases curing time and increases bonding power, no prior treatment is required.

The Araldite was produced by mixing the resin with the hardener at a ratio of 1:3.5 volume. Araldite is corrosive, and so the mixing was performed in a fume cupboard whilst wearing a lab coat and gloves. Araldite is also hazardous to the environment. Excess resin and all materials that it had touched were disposed of as hazardous waste. The bone samples were placed into

separate compartments of an ice cube tray, which were labelled with sample numbers. The Araldite mixture was poured over the samples until they were submerged, then left in a fume cupboard at room temperature for 48 hours to cure. Araldite ceases to be toxic or corrosive when hardened. The embedded bone specimens were thin sectioned using the method described above.

A minority of the ready-made samples from the Department of Archaeology's collections had previously been embedded using the LR White acrylic resin (Agar Scientific). This embedding medium would not have affected the constitution of the thin sections in a significant way, although the resin sometimes retained a slight yellow tint. The potential yellow tint was taken into consideration when the relevant samples were examined.

3.3.4 Histological Examination

All thin sections were analysed and assessed using transmitted light binocular microscopes fitted with polarising filters. Each thin section was examined at 25, 40 100 and 400 times magnification. The polarising filter enabled the examination of thin sections under cross-polarised light, which facilitated assessment of collagen fibril birefringence. All digital micrographs of bone thin sections were captured using an eye-piece mounted Lumera Infinity digital microscopy camera in conjunction with the Lumera Infinity Capture and Analyse software. Adobe Photoshop software was used to insert scale bars on the micrographs, but images were not altered in any other way.

3.4 MEASURES OF DIAGENESIS

Thin section light microscopy was the only method of analysis that was used in the current study. This technique allowed for accurate estimates of histological change and loss of the organic fraction of bone, but could not be used to infer changes to the mineral phase. However, histological analysis also allows for the recording of other diagenetic alterations to the microstructure, such as microfissures, staining, inclusions and infiltrations. The methods used for recording diagenetic features for the present project are discussed in this next section.

3.4.1 Assessment of Bioerosion

3.4.1.1 Oxford Histological Index

OHI Score	Percentage of Microstructure Remaining	Description
0	<5%	No original features identifiable, except Haversian canals.
1	<15%	Small areas of well-preserved bone present, or the lamellate structure is preserved by the pattern of destructive foci.
2	<50%	Some well-preserved bone present between destroyed areas.
3	>50%	Larger areas of well-preserved bone present.
4	>85%	Bone is fairly well preserved with minor amounts of destroyed areas.
5	>95%	Very well preserved, similar to modern bone.

Table 3.1: Oxford Histological Index (Millard 2001: 640)

The standard method of assessing bioerosion within bone thin sections is the Oxford Histological Index (OHI) (Hedges *et al.* 1995; Millard 2001). This system was originally devised by Hedges *et al.* (1995) and subsequently modified by Millard (2001) to accommodate archaeological thin sections that demonstrated medium levels of histological preservation (Table 3.1). The OHI translates an assessment of the percentage of remaining unaltered bone microstructure into an ordinal grade ranging from zero to five, representing the worst and best preserved microstructure respectively. The proportional assessments are supplemented by a description of each stage of attack (Hedges *et al.* 1995; Millard 2001).

The OHI method is subjective, although inter-observer testing performed by Hedges *et al.* (1995: 203) found that deviations were not significant and repeat assessments never differed by more than one unit. Inter and intra-observer testing of the OHI method by a postgraduate student at the University of Sheffield similarly produced no significant differences (Downey 2012). Studies of bone that have measured more than one diagenetic parameter have confirmed that OHI scores correlate with bone protein content and biomolecular loss, suggesting that they represent true underlying variation in bone degradation (Hedges et al.

1995; Nielsen-Marsh & Hedges 2000; Hedges 2002; Jans *et al.* 2004; Nielsen-Marsh *et al.* 2007). OHI scores also correspond with measures of 'm' microporosity in bone, which represent the most objective measure of microbial bioerosion (Nielsen-Marsh *et al.* 2007).

OHI scores cover the whole range of histological preservation, but do not represent equal graduations (Hedges *et al.* 1995; Millard 2001). The highest and lowest two scores represent 30% of possible variation collectively, whereas the middle two scores account for the remaining 70% (Hedges *et al.* 1995; Millard 2001). The microstructure of most archaeological bones that Hedges *et al.* (1995) used to formulate their method demonstrated very high or low levels of histological preservation, with few samples falling in the middle. The OHI system was developed to accommodate this patterning by capturing more variation at the top and bottom of the scale where most bone samples were likely to lie. The consistency in bimodal distributions of histological preservation amongst archaeological bones has been challenged by more recent studies (Nicholson 1996; Davis 1997; Millard 2001). In an assemblage where histological destruction of bone was randomly variable, a scoring system such as the OHI would bias the results towards the middle scores of two and three. The use of the OHI in the current study meant that the distribution of scores would have to be monitored to ensure that bias had not created an overrepresentation of middle values.

Studies of bone diagenesis that utilise SEM have formulated a method of bioerosion quantification that utilises image analysis software (Turner-Walker & Syversen 2002). However, the similarities between different diagenetic phenomena in thin sections observed using transmitted light microscopy would make it difficult for image analysis software to accurately identify specific regions of bioerosion. Hollund *et al.* (2012: 5) modified the OHI to take into account all diagenetic phenomena that could be detected through histological analysis, such as microfissures, which provided an overall quantified assessment of bone diagenesis (General Histological Index (GHI)). This scale would not have suited the aims of the current study, as the varied diagenetic features that Hollund *et al.* (2012: 5) recorded are likely to be influenced by several disparate factors. Their amalgamation into a single quantity would produce a variable that was influenced by too many diverse influences to be used to say anything of use, particular regarding bioerosion. The OHI was produced in order to capture variation in bioerosion specifically, which was consistent with the aims of the present study. If primary analysis of the results suggested that there was a significant correlation between bioerosion and other diagenetic features, then their combination into a single variable could be enacted at a later stage. Most studies that have investigated bone bioerosion in archaeological thin sections have used the OHI, and so the use of this method in the current

study would produce comparative data (Hedges *et al.* 1995; Nielsen-Marsh & Hedges 2000; Jans *et al.* 2004; Nielsen-Marsh *et al.* 2007; Hollund *et al.* 2012). The OHI was the only viable choice for assessing bioerosion and related histological preservation within thin sections.

A number of the archaeological thin sections from the University of Sheffield's collections had been used in previous studies of microbial bioerosion (Goodfield 1992**;** Ashford 1998; Tryzelaar 2003; Economou 2003; Davidson 2009). Most of these studies had employed novel methods of quantification, rather than the OHI. Almost all of the ready-made histological thin sections from the University of Sheffield's collections had to be assessed with the OHI for the first time for the current project. In examples where histological preservation had been assessed using the OHI, the scores for each section were reassessed by the author without prior knowledge of the original result. The old and the new scores were compared and any specimens where the two scores differed by more than one unit were discounted. Fortunately, none of the thin sections had to be excluded on this basis. In cases where there was a difference, the author's assessment was taken in order to maintain consistency with scores from the rest of the samples.

The abundance of MFD within transverse archaeological bone thin sections often varies depending on the part of the section being examined. MFD appear most commonly within sub-periosteal and sub-endosteal zones, leaving well-preserved regions of bone at the mid-section as well as at the periosteal and endosteal margins (Hanson & Buikstra 1987; Bell *et al.* 1996; Hedges 2002; Parker Pearson *et al.* 2005; Turner-Walker & Jans 2008; Hollund *et al.* 2012). The OHI was scored for the periosteal, internal and endosteal thirds in each thin section in order to capture any intra-section variability in bioerosion and to test whether there were any consistencies in the patterns of attack. Differential patterns of microbial attack might be caused by diverse diagenetic trajectories. The complete thin section was then assessed to provide a Whole OHI score.

3.4.1.2 Presence of Non-Wedl MFD

The presence of all four of Hackett's (1981) MFD types (Linear Longitudinal, Wedl, Lamellate and Budded) were recorded initially from each bone thin section. Types of tunnelling were recorded to compare their distributions to the results of other studies and to determine whether the appearance of particular MFD is influenced by discrete variables. However, it

became apparent that the linear longitudinal, lamellate and budded MFD (non-Wedl MFD) almost always appeared concurrently (Image 3.3). Previous studies of archaeological material have concluded that these tunnelling types are likely to have a shared bacterial aetiology (Bell *et al.* 1996; Jackes *et al.* 2001; Jans *et al.* 2004). The notion that the three non-Wedl MFD were representative of the same phenomena, combined with their covariance within the current study meant that it was suitable to produce a single presence/absence variable for the occurrence of all three types of non-Wedl MFD that was taken to represent the presence of bacterial bioerosion. This parameter would present a distinct record of samples where bacterial bioerosion had been entirely inhibited, which would supplement the OHI scale.

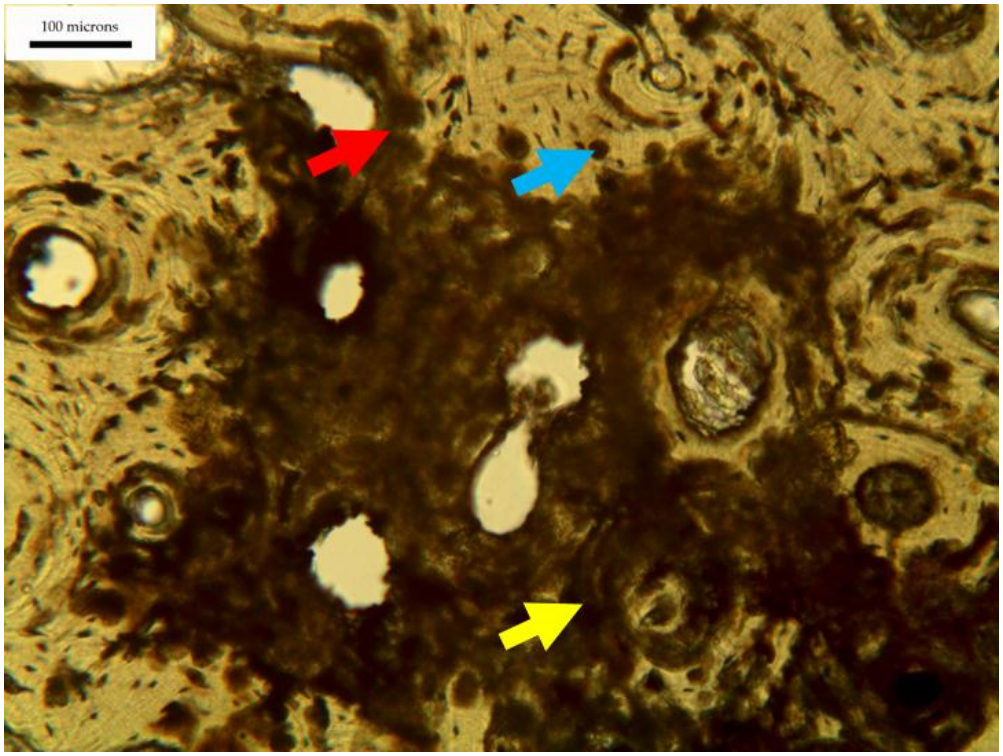

Image 3.3: Micrograph of a transverse thin section of an archaeological human femur. All three types of non-Wedl MFD can be observed in isolation and in coalescence. Red Arrow = budded, Blue Arrow = linear longitudinal, Yellow Arrow = lamellate (taken by the author).

3.4.1.3 Presence of Wedl MFD

The OHI represents a measure of all types of destructive biotic change to the bone microstructure, and it was expected that this parameter would account for any observed variation in fungal Wedl tunnelling. However, in the majority of the cases where they appeared, Wedl tunnels found within the current study sample were concentrated on small areas of bone that had been spared by the organisms that produce non-Wedl tunnelling

(Image 3.4). The limited extent of Wedl tunnels meant that they had rarely destroyed enough of the bone microstructure to register on the OHI scale. The extent of Wedl tunnelling did not vary considerably between bone samples where it was present. However, it was necessary to make some record of this form of bioerosion, as previous studies had suggested that it may be indicative of specific depositional circumstances (Jans *et al.* 2004). Therefore Wedl tunnelling was recorded within each sample on a presence/absence basis.

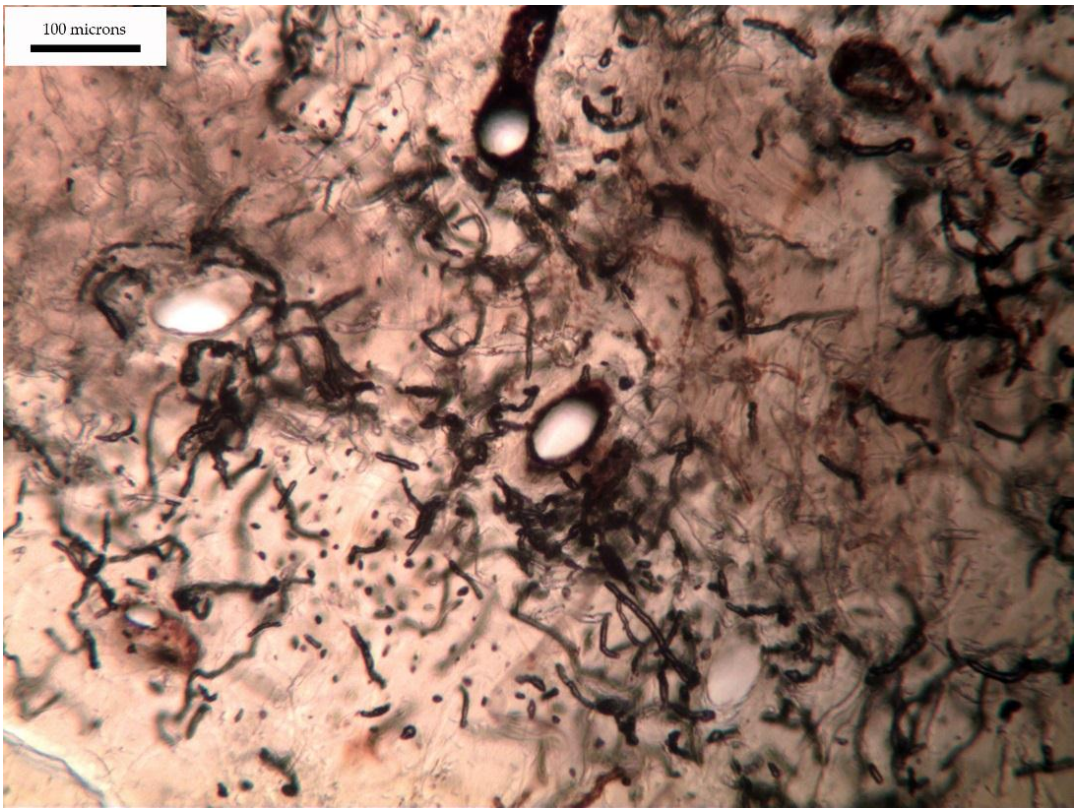

Image 3.4: Micrograph of a transverse thin section of an archaeological human femur demonstrating Wedl tunnelling in an area of the bone that had been unaffected by bacterial tunnelling (taken by the author).

3.4.2 Assessment of other Measures of Diagenetic Bone Degradation

3.4.2.1 Collagen Birefringence

The survival of collagen birefringence is commonly measured using the Birefringence Index, which affords an ordinal score depending on the intensity of fibril brightness (Jans *et al.* 2002) (Table 3.2). This method is subjective, although the low number of potential outcomes

combined with the well-defined categories suggest it is unlikely that there would be significant deviation in scores between observers (Jans *et al.* 2002). The method provided a quick and simple way of recording collagen loss.

Collagen birefringence is affected by any mechanism that removes protein from the bone, and will vary with the intensity of microbial attack (Hackett 1981). Deviations from this model could be used to infer instances where collagen has been lost by a mechanism other than bioerosion. Measures of collagen birefringence may be useful for identifying bone from circumstances which promote alternative types of collagen degradation that preserve the histological bone structure, such as Accelerated Collagen Hydrolysis (Smith *et al.* 2007). Thin sections that had lost collagen through hydrolysis would not appear degraded under normal transmitted light, but examination under polarised light would reveal a loss of birefringence. Whole samples were assessed and scored using the Birefringence Index (Jans *et al.* 2002).

Birefringence Index	Description
1	Collagen birefringence is bright and comparable to fresh bone.
0.5	Collagen birefringence is reduced.
0	Collagen birefringence has been obliterated.

Table 3.2: Birefringence Index produced using Jans et al. (2002).

3.4.2.2 Microfissures

Microfissures have most often been recorded quantitatively using the Microcracking Index (Jans *et al.* 2002). The number of osteons affected by microfissuring within a particular area are counted and the ratio of fissured/non-fissured osteons is calculated (Jans *et al.* 2002). The large number of variables that influence the frequency of microfissures combined with the difficulty in discerning the processes that cause particular kinds of fissuring meant that measurements of their abundance were not likely to have had much utility in addressing the aims of the present study. There have been no previous associations between this diagenetic parameter and early *post mortem* taphonomy. Bone bioerosion is mostly unrelated to occurrence of microfissures (Hackett 1981; Jans *et al.* 2002). The Microcracking Index is time-consuming to measure and so the use of this parameter would have potentially required a lot of work for little result (Jans *et al.* 2002).

The presence of microcracking was recorded qualitatively for each thin section. It was considered whether microfissures should have been recorded on a presence/absence basis. However, the shape, extent and distribution of microfissures differed so markedly in the small proportion of remains where they were present that a presence/absent system seemed inappropriate. The futility of recording microfissures was increased by the likelihood that they had various possible causes (Jans *et al.* 2002). Qualitative descriptions of microfissures were produced for each bone thin section and employed in the site-specific discussions of bone diagenesis, but no quantitative recording systems was employed. These descriptions did not form part of the main analysis, but were employed in site-specific discussions of bone histology in cases where they aided interpretations of diagenetic patterns.

3.4.2.3 Persistence of the Periosteal surface

A common observation amongst studies of archaeological bone thin sections is that the periosteal and endosteal fringes of bone thin sections persevere regardless of the histological preservation of the bone cross-section as a whole (Hanson & Buikstra 1987; Nielsen-Marsh & Hedges 2000; Hedges 2002; Jans *et al.* 2004; Hollund *et al.* 2012) (Image 3.5). Studies that discuss this observation do not provide any specific information regarding its prevalence (Hanson & Buikstra 1987; Hedges *et al.* 1995; Hedges 2002; Jans *et al.* 2004). The presence of a preserved periosteal surface was recorded in each sample using a binary system to measure its frequency and determine whether it is independent of other parameters of bone diagenesis. The measurement of this variable may have some bearing on the interpretations of diagenetic signatures.

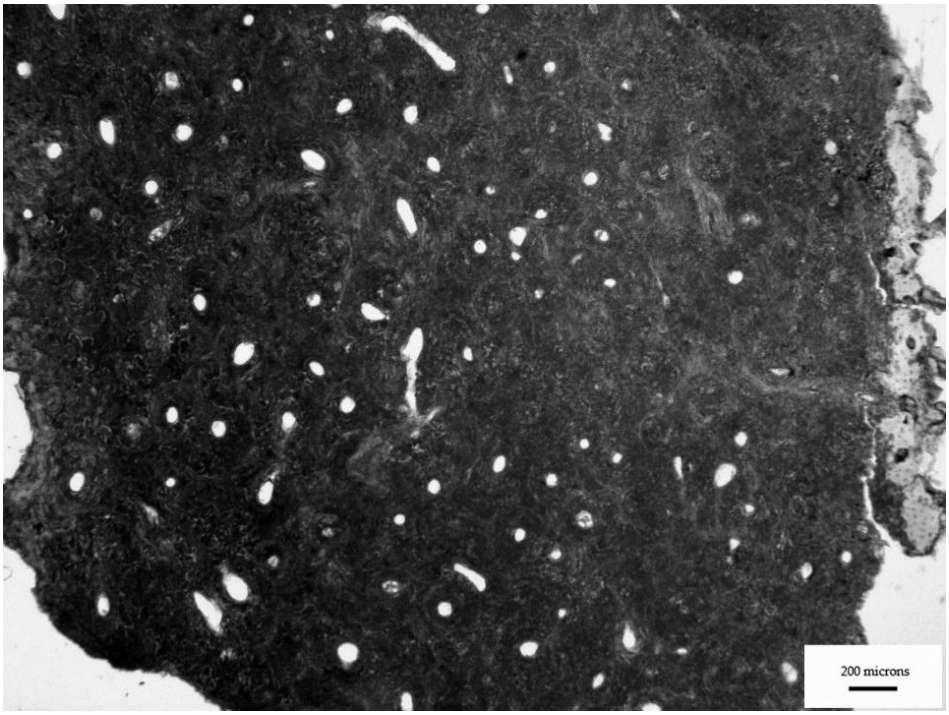

Image 3.5: Micrograph of an archaeological human femoral transverse thin section. The histological preservation of the periosteal surface persists despite the rest of the sample having been intensively tunnelled (taken by the author).

3.4.3 Visual Diagenetic Changes

Visual diagenetic changes, consisting of staining, inclusions and infiltrations, represent factors that alter the appearance of the bone microstructure but do not necessarily contribute to histological degradation. Visual diagenetic changes are usually taken to represent the results of interactions between the bone and minerals contained within the external burial environment (Garland 1987; 1993; Grupe & Dreses-Werringloer 1993; Gross *et al.* 1997; Schultz 1997; Turner-Walker 1999; Hanson & Cain 2007; Turner-Walker & Jans 2008; Hollund *et al.* 2012). It was pertinent to produce a record of the visual diagenetic features present within each bone sample, as their nature and extent were likely to reflect the composition of the depositional environment (Turner-Walker & Jans 2008; Hollund *et al.* 2012). Assessment of these features would produce a more rounded analysis of bone diagenesis and provide insight into how the bone sample had interacted with its burial context (Turner-Walker 1999; Turner-Walker & Jans 2008; Hollund *et al.* 2012). A test of the association between the occurrence of these variables and measures of bone degradation would help control for environmental effects on bioerosion.

The presence or absence of particular forms of staining, inclusions and infiltrations could also be used to deduce whether a body originally decomposed under anoxic conditions through the identification of pyrite inclusions and orange iron oxide staining (Turner-Walker 1999; Turner-Walker & Jans 2008; Hollund *et al.* 2012). No method of quantification has yet been developed for recording the presence of visual diagenetic features within archaeological bone thin sections. These features were recorded descriptively, and a method of quantification was developed based on these observations. This approach meant that it was possible that the methods of quantification used in the current study would only be applicable to this specific study sample.

3.4.3.1 Staining

Staining in all samples could be classified by colour as orange, yellow and brown. The colour of staining was constant across most bone samples. Variation in staining colour observed within a thin section was usually a result of diversity in a single colour. A small proportion of samples which demonstrated different intensities of staining included all three colours and it was possible that all types were the product of the same process or element. The extent of staining could be classified within one of four categories (Table 3.3). Staining Scores were recorded for each separate colour in present in each sample.

Score	Assessment	Description
0	None	No staining visible
1	Superficial	Staining is concentrated exclusively at the periosteal and endosteal surfaces.
2	Fair	Staining is present at periosteal and endosteal surfaces as well as within internal osteons.
3	Extensive	Staining is present throughout the microstructure.

Table 3.3: Outline of the Staining Score method.

3.4.3.2 Inclusions

Inclusions consisted of material deposited within the natural bone porosities. Qualitative recording of inclusions revealed that there was little variation in their colour and morphology across all samples. Most inclusions consisted of amorphous coarse orange or brown accumulations. The material became more opaque when it had collected in high densities within porosities and appeared almost black in certain samples. Gradation between the orange, brown and black colour of inclusions could be observed within single thin sections and sometimes within single porosities, which confirmed that these three colours represented the same material. These features were labelled 'Orange' inclusions, although it should be stressed that this label represented a convenient classification of a ubiquitous granular substance whose colour could vary from orange to brown to black. A second type of inclusion observed in a minority of samples consisted of large grey or transparent structures. These 'Grey' inclusions tended to appear in isolation filling the Haversian canal and resembled a solid mass rather than an accumulation of smaller grains. The frequency of inclusions within sections could be classified within one of four ordinal categories; none, infrequent, frequent and pervasive (Table 3.4). This variable was recorded for each colour category in each sample.

Score	Assessment	Description
0	None	No inclusions observable.
1	Infrequent	Inclusions were visible in the minority of microporosities that could be observed.
2	Frequent	Inclusions were visible in the majority of microporosities that could be observed.
3	Pervasive	Inclusions were present in almost every observable microporosity.

Table 3.4: Description of the method used for scoring the frequency of inclusions.

3.4.3.3 Infiltrations

Infiltrations consisted of materials that had been deposited within the bone matrix rather than natural porosities. Infiltrations within all thin sections consisted of orange and black particles of material. These two colours were present within all thin sections that demonstrated infiltrations, and could not be meaningfully separated. The extent of infiltrations did not vary

significantly. These features usually appeared around porosities that were densely packed with inclusions. It was possible that the limitations of the thin section microscopy method meant that the different types of infiltrations could not be discerned. The lack of variation in the type and extent of infiltrations meant that they had to be measured on a presence/absence basis.

3.5 Recording of Variables that Potentially Influenced Bone Diagenesis

There are a variety of factors that could potentially affect diagenetic interactions (Rodriguez & Bass 1983; 1985; Mann *et al.* 1990; Campobasso *et al.* 2001; Wilson *et al.* 2007; Vass 2011; Zhou *et al.* 2011). The nature of the archaeological material meant that it was impossible to control for all of these features whilst retaining a useful sample size. The aims of the current study dictated that if there was a significant relationship between funerary treatment and bone bioerosion, then most features would not have significantly influenced levels of bacterial attack in bone. However it was important that at least some of these potential influences were considered and assessed when interpreting the results of measures of bone bioerosion.

With regards to other measures of bone diagenesis, the extent to which recorded influential factors could be perceived to have influenced bone diagenesis would dictate whether the relationship between diagenesis and early taphonomy was strong enough to suggest that microscopic examination of bone would be useful in determining the nature of funerary processes. Therefore, there was some attempt to record the main factors that were likely to have affected putrefactive decomposition and bone diagenesis. This preparation included strategies to anticipate the possibility of bone bioerosion having been caused by exogenous bacteria.

3.5.1 Environmental Factors

3.5.1.1 Soil Type

Previous microstructural studies of archaeological bones from across varied sites established that the intrinsic physical and chemical properties of the burial environment have no effect on overall levels of bone bioerosion, although it was unknown how these factors may have affected other type of bone diagenesis (Hanson & Buikstra 1987; Nielsen-Marsh e al. 2007;

Smith *et al.* 2007). The present study did not have the time nor resources to conduct similar tests on soils that had surrounded every bone that was sampled. The sites that were included in the current study sample were scattered around the country and had been excavated at different times. The bones from these sites had been recovered from a variety of different sediment types. It was unclear whether burial soil samples from every site would have been extant or accessible.

It was necessary to include some record of the burial conditions of each site to ensure that soil composition had not affected the way in which the archaeological bone had been bioeroded, either through the actions of exogenous microorganisms, or by soil properties interfering with enteric decomposition. Measurement of soil type was also necessary to address variation in other diagenetic factors that were to be recorded, such as staining, inclusions and infiltrations. If any of these microstructural features varied consistently with bioerosion, it would be important to establish why, and whether this variation was related to treatment of the body or burial environment. The way in which each site report had recorded burial sediment varied widely. The exact wordings of the reports regarding the burial sediments were recorded initially for each sample.

After all of the burial sediments had been catalogued for each site, attempts were made to develop a system that could be used to classify similar soils. The sediments could be split into one of four broad categories; sand, silt, clay or gravel. Bones from one site had never been buried in sediment and were allocated a separate category of 'open'. The other categories crudely represented collective features of each soil, such as coarseness of soil particles (Figure 3.1). These features would have dictated intrinsic factors of the soil that may have interfered within early bodily decomposition or abundance and composition of soil microbiota, such as soil aeration, drainage and composition (Rodriguez & Bass 1985; Janaway 1996; Dent *et al.* 2004). The likely effect that these properties had on soil hydrology meant that it was probable they had some bearing on other types of diagenetic change (Nielsen-Marsh & Hedges 2000). These categorisations of soil type were rudimentary, but represented the best possible scenario in capturing variation between the sites used in the current study.

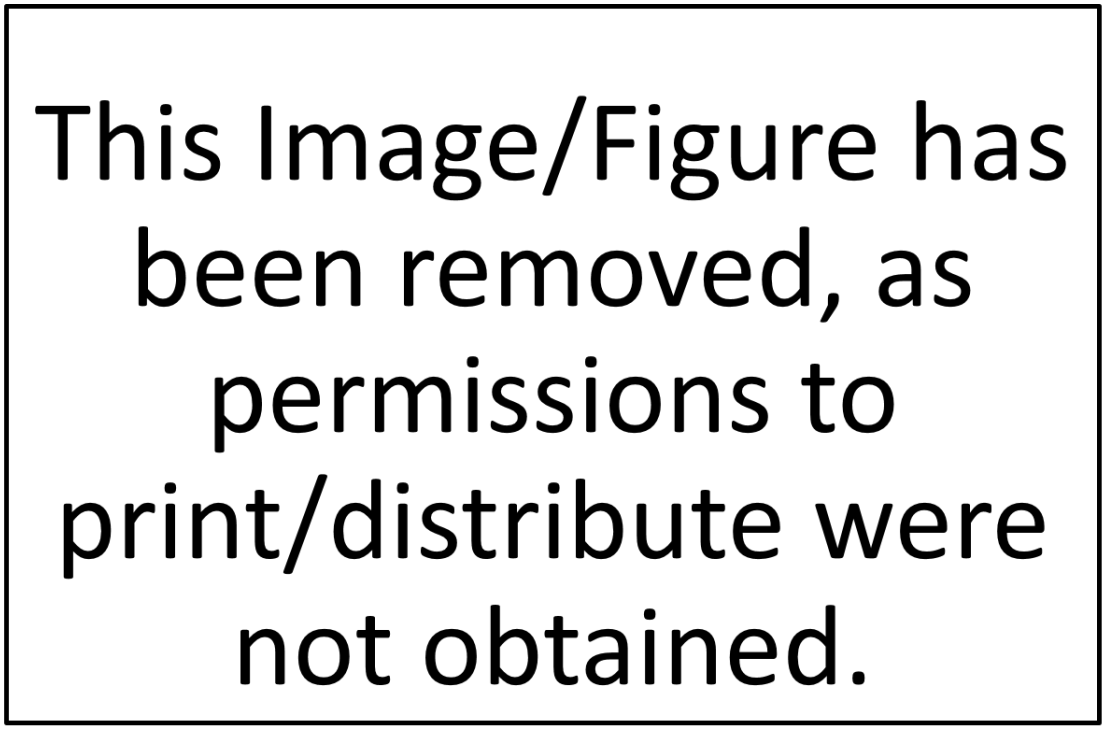

Figure 3.1: Diagram of variation in soil texture used as a basis for the classification of soil types (Janaway 1996: 59).

It was originally intended that some measurement of soil pH would also be included. Soil pH has been found to affect bodily decomposition and microbial load of the soil (Manhein 1997; Haslam & Tibbett 2009). However, studies by Hanson & Buikstra (1987), Nielsen-Marsh *et al.* (2007) and Smith *et al.* (2007) all established that whilst overall bone diagenesis is heavily influenced by soil chemistry, measures of bioerosion did not fluctuate with variations in pH. A record of pH was still desirable in order to test this association within the bone assemblage that was used. Unfortunately, most site reports did not include specific measures of pH. Where pH was mentioned, soil types were usually classified broadly as neutral, alkaline or acidic. It was considered whether this three-category division could be used for the present study. It was thought that absent values could have been filled by regional results of nationwide surveys of soil pH. Unfortunately, the soil pH surveys were too imprecise to provide reliable soil pH values for specific archaeological sites.

The next strategy that was considered involved inferring soil pH from the bedrock geology (Laslett *et al.* 1987; McGraph & Loveland 1992). Soils usually reflect the pH of their parent geology (Laslett *et al.* 1987; McGraph & Loveland 1992). Soils are also in constant mineral exchange with their underlying bedrock, and so geology will always influence overlying soil pH

to some extent (Laslett *et al.* 1987; McGraph & Loveland 1992). However, soil pH can also be affected by a large number of other natural and anthropogenic factors (Laslett *et al.* 1987; McGraph & Loveland 1992). After some attempts were made to discern soil pH from geology at a selection of sites, this system was deemed too complicated, time-consuming and unreliable for use in the present study.

The three category system of classifying soil pH was also reconsidered, as it would have created a false division between soils that were quite similar. The pH of the soils that preserved archaeological bone had to be alkaline or close to neutral in order for the material to have survived into the archaeological record (Gordon & Buikstra 1981; Bethel & Carver 1987; Nielsen-Marsh *et al.* 2000; Smith *et al.* 2007). Any system that discriminated between neutral and acidic soils would have created a false notion of distance, as the rarity of highly alkaline burial environments would have ensured that soil pH only varied from slightly acidic to moderately alkaline (Smith *et al.* 2007). These variations would not have been captured appropriately with categories of alkaline, neutral and acidic, as overall pH scores were likely to have been quite similar in terms of how they affected bodily decomposition and subsequent bone diagenesis (Haslam & Tibbett 2009). It was decided that there was no requirement to attempt to record soil pH for the current study, as the relationship between this factor and bone diagenesis had already been established using precise techniques. Any attempts to record soil pH were likely to have been simplistic and inaccurate in comparison (Hanson & Buikstra 1987; Nielsen-Marsh *et al.* 2007; Smith *et al.* 2007). The use of bone samples from dispersed archaeological site meant that if diagenesis varied significantly with changes in soil pH across the archaeological sites used in the current study, then the hypotheses set out in the Methodology would be invalidated.

3.5.1.2 Anoxic Environments

The overriding effect of anoxic environments on bodily decomposition and bacterial bone bioerosion meant that the potential influence of anoxic sediments had to be considered when interpreting the diagenetic signatures of the bones used in the current study (Polson *et al.* 1985; Janaway 1996; Bottrell *et al.* 1998; Turner & Wiltshire 1999; Fielder & Graw 2003; Dent *et al.* 2004; Turner-Walker & Jans 2008; Vass 2011; Hollund *et al.* 2012). Anoxic environments can also influence visual diagenetic changes and non-biotic histological degradation (Turner-Walker & Jans 2008; Hollund *et al.* 2012). Bones from individuals that had decomposed within

waterlogged or anoxic environments would be expected to demonstrate high levels of histological preservation compared to those that had decomposed in an aerated environment (Turner-Walker 1999; Turner-Walker & Jans 2008; Hollund *et al.* 2012). Under an endogenous model, bacterial bone bioerosion would only be affected by environmental anoxia that occurred whilst the body was decomposing. In cases where bodies had been surrounded by a dense sediment that was intrinsically anoxic from the point of deposition, it could be assumed that the body had decomposed anaerobically (Turner & Wiltshire 1999; Hollund *et al.* 2012).

Anoxia promoted by waterlogging tends to be episodic and linked to the depth of burial, height of the water table or efficiency of soil drainage (Björdel *et al.* 2000; Powell *et al.* 2001; Holden *et al.* 2006). Environmental or anthropogenic changes that alter the height of the water table can render previously waterlogged anoxic environments as aerobic and vice versa (Björdel *et al.* 2000; Powell *et al.* 2001; Holden *et al.* 2006). The state of the burial sediments at the point when a skeleton was recovered could not be taken to reflect their state when the body was buried (Turner-Walker & Jans 2008). Early anaerobic decomposition could be inferred in cases where there was some survival or organic tissue and grave goods, as decomposition must have been affected by anoxia within the early *post mortem* period (Janaway 1996; Björdel *et al.* 2000; Powell *et al.* 2001; Holden *et al.* 2006). However, an absence of organic preservation could not be used to infer that there had been no previous environmental anoxia, as soft tissue and grave goods preserved during initial waterlogging could have then been lost when the environment became aerobic. Evidence for waterlogging at the point of recovery was not enough to assume that a body had decomposed under these conditions, as inundation may have been a recent occurrence.

Anaerobic conditions were recorded on a presence/absence basis in cases where either the burial sediment was intrinsically anoxic, or there was evidence for waterlogging alongside survival of organic material from the point of burial. This record would allow for a test of the effects of anoxic conditions and whether they overshadowed any relationship between bone diagenesis and funerary treatment. It was possible that some of the skeletons that were classified as having originated from aerobic contexts had actually been interred initially within anaerobic environments, and vice versa. There was no way to counter-act this problem. The environmental circumstances and histories of any bones from aerobic contexts that demonstrated histological signatures consistent with anaerobic decomposition would have to be scrutinised at a later stage.

3.5.1.3 Climate & Season of Death

Season of death cannot be determined or controlled for most archaeological human remains. However, significant relationships between seasonality and bone bioerosion would be apparent within the histological signatures of bones from all sites. Decomposition of buried and unburied remains is fastest in warmer months (Rodriguez & Bass 1983; 1985; Mant 1987; Galloway *et al.* 1989; Manhein 1997; Rodriguez 1997; Campobasso *et al.* 2001; Dent *et al.* 2004; Carter *et al.* 2007; Wilson *et al.* 2007; Vass 2011; Meyer *et al.* 2013). If putrefaction and patterns of bone bioerosion were primarily dictated by season of burial, it would be expected that the whole spectrum of putrefactive bioerosion would be represented within each site assemblage. Barring any underlying biases in season of decomposition between Historical and Later Prehistoric remains, it would be unlikely that the hypotheses set out in the Background chapter (page 98) would be substantiated if season of death significantly affected bone bioerosion.

The possible effect of climatic fluctuations on bacterial bone bioerosion emphasised the importance of keeping the study area within the confines of temperate Europe. These restrictions would ensure that the remains sampled for this project had decomposed under similar climatic conditions. Climate across the U.K. and temperate Europe varies to some extent but forensic studies suggest that this variation would not have altered decomposition rates significantly (Rodriguez & Bass 1983; 1985; Mant 1987; Galloway *et al.* 1989; Manhein 1997; Rodriguez 1997; Campobasso *et al.* 2001; Dent *et al.* 2004; Carter *et al.* 2007; Wilson *et al.* 2007; Vass 2011; Meyer *et al.* 2013). Any variation in putrefactive bone bioerosion attributable to climatological variability should be apparent within a spatial distribution by latitude.

The climate of the U.K and temperate Europe has varied over Late Prehistoric and Historical periods. There is little that can be done to address this problem, as remains from all periods had to be included if this project was to obtain representations of variable rites. The temporality of climatic conditions would have to be taken into account when the results are interpreted. It would be expected that there would be notable phase-specific patterns in bone bioerosion of the Historical remains if temporal changes in climate had significantly influenced bone bioerosion.

3.5.1.4 Cave Environments

Some of the Later Prehistoric remains sampled for the current project had been recovered from caves. Most of the bones from cave sites had been disarticulated, although there was evidence to suggest that the whole bodies had decomposed within the cave environment (Chamberlain 1999). It was possible that the specific type of indoor bodily decomposition that occurs within a cave environment would produce a characteristic signature of putrefactive bone bioerosion (Galloway *et al.* 1989; Goff 1991; Terrell-Nield & MacDonald 1997; Anderson 2011). A cave is a unique environment that might instigate similarly unique diagenetic changes to the bone microstructure. Bones from bodies that had probably decomposed within a cave were recorded using a presence/absence system.

3.5.2 Anthropogenic Factors

3.5.2.1 Clothing & Wrappings

It might be expected that a relationship between clothing and putrefactive bone bioerosion would be of benefit to the aims of this project in terms of discerning funerary behaviour. However, significant correlations between bone bioerosion and clothing would invalidate the assumptions regarding the diagenetic consistency of the Historical bones, particularly because the presence of such items is difficult to determine and could not be controlled. The hypotheses set out in the Discussion chapter assumed that wrappings or clothing would only affect putrefactive bone bioerosion in a limited capacity, if at all (Mant 1987; Galloway *et al.* 1989; Garland & Janaway 1989; Mann *et al.* 1990; Goff 1992; Aturaliya & Lukasewycz 1999; Campobasso *et al.* 2001; Fielder & Graw 2003; Kelly *et al.* 2009; Vass 2011; Voss *et al.* 2011; Fereira & Cunha 2013).

Proponents of the archaeothanatology (archaeology of death) method have developed techniques for identifying skeletons that had previously been wrapped (Duday 2006; Nilsson Stutz 2006). Wrapping holds the joints in unstable positions during soft tissue decomposition and soil infilling, producing a 'walling' effect on the skeleton (Duday 2006; Nilsson Stutz 2006) (Figure 3.2). *In situ* plans or photographs were available for the articulated samples that were sampled for the current project, and so it was possible that each skeleton could have been checked for signs of walling. However, this attitude would not be present within every skeleton that was wrapped, and certainly not in most that were clothed. Loose wrappings or clothing

would not hold the bones tightly enough to produce the unstable skeletal positions that characterise walling.

Attempts to control for the presence of wrappings or clothing amongst the samples used in this project would probably be inaccurate. If wrappings did exert an influence on bacterial bone bioerosion, the relationship observed between wrappings and bodily decomposition suggests that they would limit levels of putrefactive bone bioerosion. The variation in period of burial of the Historical remains sampled for the current project ensured that bodies were likely to have been variably wrapped in shrouds or dressed in clothes. The hypotheses regarding the consistency and nature of bacterial bioerosion within Historical burials should be falsified if wrappings or clothes had significantly affected this parameter.

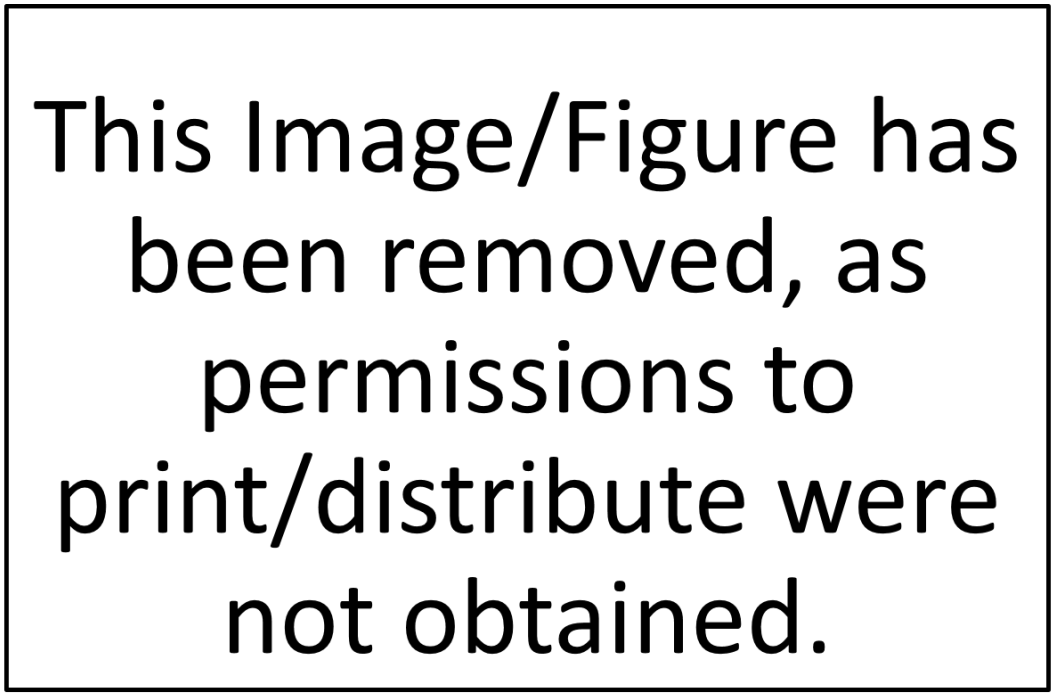

Figure 3.2: The walling effect in a previously-wrapped Mesolithic skeleton from Vedbæk-Bøgebakken, Sweden (Stutz 2006: 4).

3.5.2.2 Coffin Burial

The ability to identify coffined burials from bone histology would appear to support the aims of the current project. However, suggestions from forensic and archaeological studies that the type of coffin burial afforded to the majority of individuals in the past would not have significantly affected putrefaction meant that the hypotheses assumed that coffin burial would

not have affected bacterial bone bioerosion (Rodriguez & Bass 1985; Mant 1987; Mann *et al.* 1990; Owsley & Compton 1997: Fielder & Graw 2003; Jans *et al.* 2004; Nielsen-Marsh *et al.* 2007; Fereira & Cunha 2013). Metal fittings or paraphernalia such as coffin plates sometimes survive into the archaeological record (Brothwell 1981). In some cases a charcoal outline of the original timber coffin survives in grave cuts (Brothwell 1981). However, the inconsistency in the survival or recovery of these fittings or stains meant that any attempt to control for the presence of coffin would be inaccurate.

The previous presence of a coffin in a grave may be inferred by the position of the body and the way a skeleton collapsed during decomposition (Duday 2006; Nilsson Stutz 2006). If the coffin was narrow, the bones of the body would have been held in an unstable position during soft tissue decomposition and soil infilling, which would produce a walling effect on the skeleton (Duday 2006). A large coffin would have surrounded the body with an open cavity, causing the skeleton to collapse outside of the corpse's silhouette during decomposition (Duday 2006). In grave cuts that contain multiple burials, the collapse of an underlying coffin can be inferred by slumping of the grave bottom (Brothwell 1981). None of these methods could consistently be used to identify the presence of a coffin within a particular grave, therefore it was difficult to control for coffin burial.

The Historical assemblage was gathered from a variety of sites that demonstrated variable evidence for coffin burial. As inhumation exposes the bone to the highest levels of putrefactive decay, coffin burial would have had to have inhibited putrefaction to have produced a detectable change in bacterial bone bioerosion. Therefore, if coffin burial were a major factor that affected bodily decomposition and bone bioerosion, the hypotheses regarding the consistency of Historical bone bioerosion would be expected to be falsified. The presence of coffins with certain remains was recorded on a presence/absence basis in those sites where their incidence could be confidently ascribed and measures of related bacterial bone bioerosion were interpreted on a site-by-site basis.

3.5.2.3 State of Articulation

It was expected that all buried articulated remains, regardless of archaeological phase, would demonstrate similar patterns of bacterial bone bioerosion because this rite represents the primary way that an articulated skeleton survives into the archaeological record. A variety of different processes may have been responsible for the disarticulation of Later Prehistoric

remains, and so it was predicted that significant variation in bone bioerosion amongst bones from these phases would be explained by the disarticulated samples. The state of the remains was recorded in order to account for variation in measures of diagenesis and test these predictions.

An attempt was made to set up a gradated system of skeletal articulation that ranged from articulated, through various stages of partial disarticulation, to an entirely disarticulated skeletal element. However, it became clear that there was an almost limitless number of possible gradations that could be generated to account for the variation in skeletal articulation amongst the study sample (Image 3.6). It was difficult to gauge what resolution of separation was appropriate for reflecting different treatments that would have had a variable effect on skeletal articulation and bone diagenesis. This lack of knowledge meant that the best approach was to be conservative and classify the state of remains based on what could be known for certain. Therefore, bones samples were grouped by state based upon whether they were likely to have been permanently buried soon after death (articulated) or treated to any other process (disarticulated). This system of categorisation meant that the state of the remains represented in the disarticulated category varied widely, from almost complete individuals to completely disarticulated elements. This situation was not ideal, but was considered to be the best way of dealing with the unknowns regarding how variably-disarticulated remains came to be disassembled.

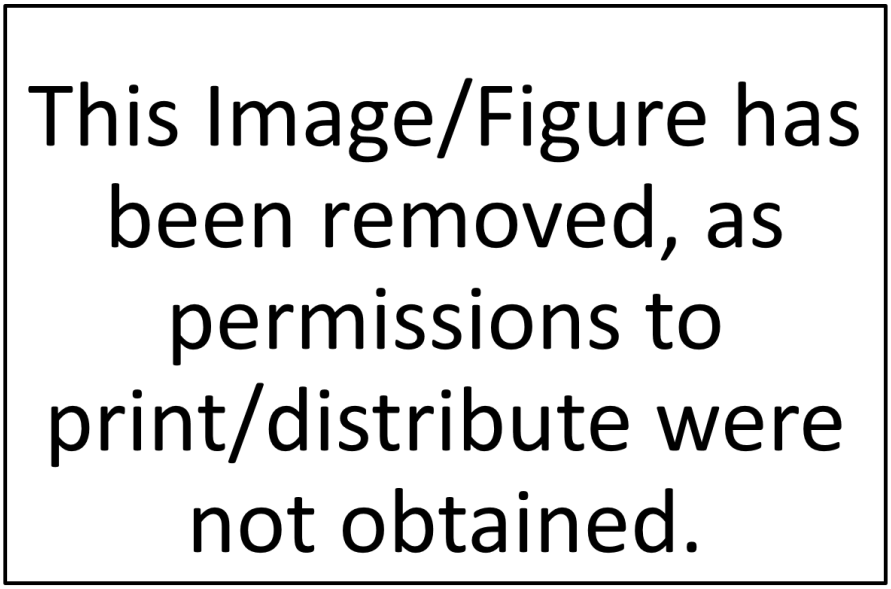

Image 3.6: Photograph of the charnel pit P923 from the Danebury Iron Age hillfort in Hampshire, U.K. Several different stages of skeletal articulation can be observed amongst the human remains (Cunliffe 1984: 447).

3.5.2.4 Historical Charnel Material

The use of disarticulated material from Historical periods was valid for the purposes of the current study. All of the Historical disarticulated material that was held at the Department of Archaeology consisted of either parts of disturbed burials recovered from historical grave fills or formal charnel deposits (Image 3.7). Disarticulated skeletal material recovered from grave fills is most often interpreted as remains disturbed by new grave digging (Daniell 1997). The nature of formal British charnel deposits is debateable, but they are most often thought to represent the reburial of disarticulated remains from bodies that had fully decomposed (Daniell 1997). In both cases, the early depositional circumstances of each disarticulated individual would have involved inhumation soon after death and would be consistent with the other Historical articulated specimens. Some of the Historical disarticulated examples used in the current study were recovered in partial articulation, which suggested that the soft tissues of each individual had not decayed completely before their bones were disturbed. It was unlikely that the disturbance of remains at a late stage would have affected putrefactive bone bioerosion (Adlam & Simmons 2007).

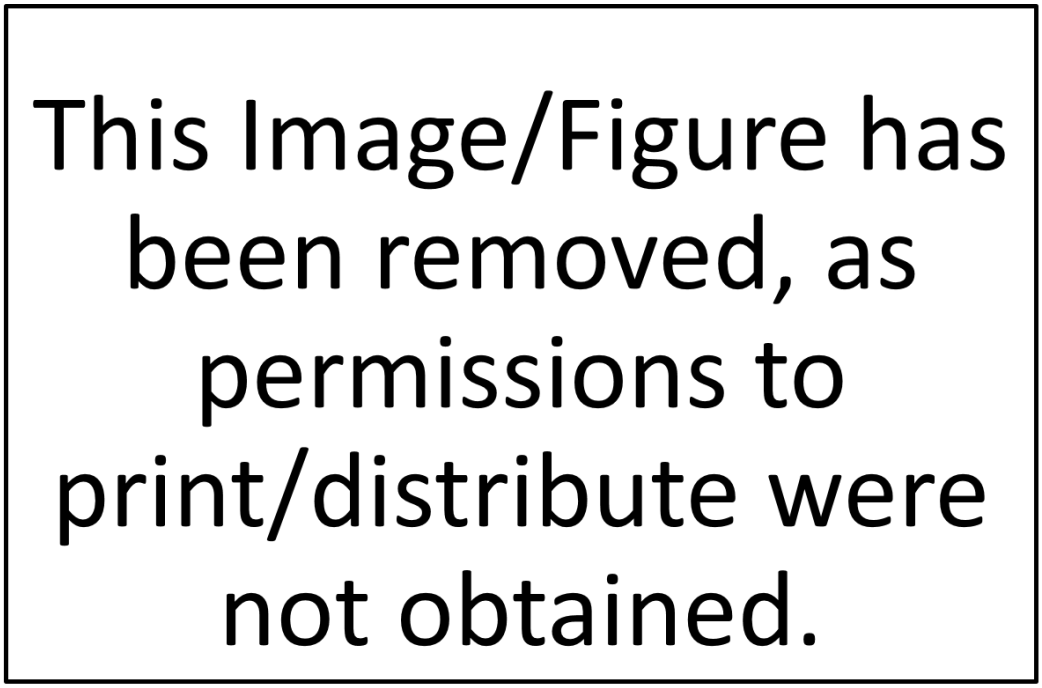

Image 3.7: Historical charnel pit from St. Helen-on-the-Walls in York (Daniell 1997: Plate 7).

Investigator disturbance of unburied remains has been shown to have little effect on decomposition (Adlam & Simmons 2007; De Jong *et al.* 2011). Disturbance of remains that were actively decomposing in graves is likely to have had a larger effect on decomposition, as exhumation alters the specific microenvironment of a cadaver (Janaway 2006; Wilson *et al.* 2007). The results from the charnel material would be tested at the analytical stage to check whether disturbed bones retained particular patterns of bone diagenesis. If significant differences between the articulated and disarticulated Historical samples were observed, the disarticulated charnel would be excluded.

The use of disarticulated Historical remains was consistent with attempts to ensure that destructive sampling of bone had the least overall detrimental effect on the research potential of assemblages. Comingled, unphased, disarticulated human remains are considered to have a smaller breadth of research potential than bones that constitute parts of whole individuals recovered in articulation from discrete graves (Brickley & McKinley 2004). Larger proportions of the disarticulated bones had also been fragmented, which increased their attractiveness for destructive analysis on the grounds of preserving research potential. Larger number of samples were permitted to be taken from disarticulated assemblages than what would have been allowed from groups of whole articulated skeletons. Some of the disarticulated Historical material had already been sampled for past research projects and so the inclusion of this category of materials was unavoidable if sample size was to be maximised.

3.5.2.5 Burial Depth

Burial depth was recorded sporadically and variably amongst the reports of the sites that were included in the current project. Values were not always comparable between sites and it was not possible to record burial depth in a consistent away across the entire study sample. The requirement to ensure that a body lies deep enough below the ground to avoid disturbance by scavenging carnivores, but not too deep to require an inordinate amount of work, meant that the majority of the individuals whose bones were used in the current study had been interred at depths that would probably not have significantly interfered with bodily decomposition (Rodriguez & Bass 1985; Garland & Janaway 1989; Mann *et al.* 1990; Janaway 1996; Campobasso *et al.* 2001; Dent *et al.* 2004; Vass 2011). However, information from site reports which suggested that particular burials had been placed deeply or shallowly was noted and discussed in relation to site-specific interpretations of bone diagenesis. Burial death would

inevitably vary within and between different site assemblages and therefore it was unlikely that the hypotheses regarding bacterial bioerosion would be supported if this factor had significantly affected putrefactive attack to bone.

3.5.2.6 Cremated Bone

Cremation produces a unique diagenetic signature in bone (Forbes 1941; Stiner *et al.* 1995; Hanson & Cain 2007; Pijoan *et al.* 2007; Squires *et al.* 2011). The intensity of burning that is required for a bone to have calcinated would dictate that all cremated bone would be unattractive to osteolytic bacteria due to the loss of collagen. Intense burning causes the rapid evaporation of moisture and degradation of the protein molecules (Forbes 1941; Stiner *et al.* 1995; Hanson & Cain 2007; Pijoan *et al.* 2007; Squires *et al.* 2011). Complete calcination of bone results in an object that is predominantly inorganic (McKinley 2000).

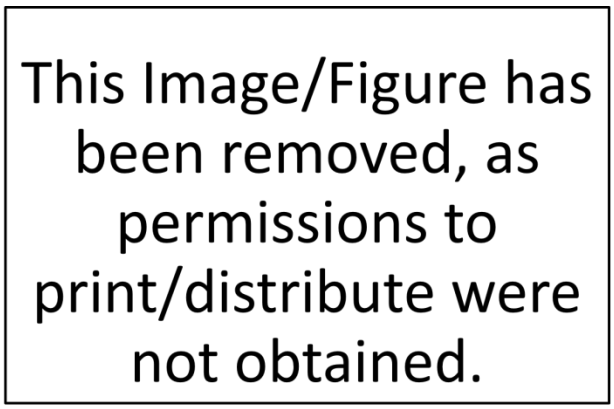

Image 3.8: Micrograph of a transverse thin section of an Anglo-Saxon cremated human bone fragment from Elsham, Lincolnshire. The microstructure has been severely altered as a result of carbon infiltration, protein loss and hydroxyapatite crystal fusion (Squires et al. 2011: 2404).

If the bone was cremated after having previously skeletonised, any bioerosion would probably not be detectable because of the changes to the bone microstructure produced by cremation (Image 3.8). Cremation fills the bone microstructure with particles of carbon (Stiner *et al.* 2005; Hanson & Cain 2007). As temperature and duration of burning increases, so does the volume of carbon, until microstructural features are almost unrecognisable (Stiner *et al.* 2005; Hanson & Cain 2007). The fusion of the bone mineral crystals that occurs at high temperatures warps and alters the colour of the microstructures (Hanson & Cain 2007). The loss of bone volume promoted by evaporation causes bone shrinkage and the collapse of the

microstructure into any available natural porosities (Hanson & Cain 2007). The osteocyte lacunae are usually the first natural porosities to disappear (Forbes 1941; Stiner *et al.* 1995; Hanson & Cain 2007). The morphology of any previous biotic tunnelling would be expected to be lost or transformed by similar processes. Histomorphological studies of cremated bone have not detected any forms of bioerosion (Forbes 1941; Stiner *et al.* 1995; Hanson & Cain 2007; Pijoan *et al.* 2007; Squires *et al.* 2011). Studies of diagenesis within cremated bone would not be tenable. Cremated bone could not be used for the purposes of the current study.

3.5.3 Demographic Factors

3.5.3.1 Age

Turner-Walker (2008) suggested that variation in bacterial bioerosion may be attributable to age-related differences in the bone microstructure dictating the speed and intensity of microbial attack (Kerley 1965; Kerley & Ubelaker 1978; Frost 1987; Cattaneo *et al.* 1999; Maat *et al.* 2006). Remodelling that takes place over an individual's lifetime steadily increases the porosity of the bone because of the accumulation of secondary osteonal bone (Kerley 1965; Kerley & Ubelaker 1978; Frost 1987; Cattaneo *et al.* 1999; Maat *et al.* 2006). Bone remodelling rates are particularly high amongst adolescents (Junqeuira et al 1986). Observations that the logistics of osteolytic bacterial invasion are dictated by features of the bone microarchitecture suggest that the extent of bacterial bioerosion might be dictated by age-at-death of an individual (Child 1995a; 1995b; Bell *et al.* 1996; Jans *et al.* 2004; Hollund *et al.* 2012; Turner-Walker 2012). The effect of bone porosity on interactions between the bone and the external environment suggests that demographic factors may affect other types of diagenetic change.

The bodies of neonatal individuals decompose differently to those of post-neonatal remains, and White (2009) found that neonatal pig bone was more likely to demonstrate lower levels of bacterial bioerosion than similarly-treated post-neonatal remains (Polson *et al.* 1985; Mant *et al.* 1990; Campobasso *et al.* 2001). This pattern was repeated when White (2009) analysed a sample of archaeological skeletal material. These patterns of decomposition were explained by the lower levels of intestinal microbiota present within new-born individuals, which pre-empted putrefactive bacterial invasion of bone (Mackie *et al.* 1999; White 2009).

All of the skeletons whose bones were used in the present study had been assessed using modern standardised osteological methods. Aging of all adult remains was based upon one or

a combination of dental development/attrition, epiphyseal fusion, cranial suture closure, changes to the pubic symphysis, the sternal portion of the ribs and the auricular surfaces of the ilium (Krogman 1955; Moorees *et al.* 1963; Miles 1963; Maresh 1970; Gustafson and Koch 1974; Scheuer *et al.* 1980; Brothwell 1981; Isçan *et al.* 1984; Smith 1984; Isçan *et al.* 1985a; 1985b; Lovejoy *et al.* 1985, Meindl & Lovejoy 1985; Krogman & Isçan 1986; Steele & Bramblett 1988; Bouts & Pot 1989; Ubelaker 1989; Brooks & Suchey 1990; Smith 1991; Buikstra & Ubelaker 1994; Bass 1995; Schwartz 1995; Buckberry & Chamberlain; Scheuer and Black 2000; Brickley & McKinley 2004). Aging of sub-adults was based on combinations of diaphyseal length, epiphyseal fusion, dental development and dental attrition (Fazekas & Kosa 1978; Scheuer *et al.* 1980; Isçan *et al.* 1984; Scheuer & Black 2000).

The use of human skeletal remains from a number of different sites meant that age-at-death estimates had been produced using variable methodologies and categories. The methods used were dependent on the state of the assemblage, osteologist preference and stage of development in osteological techniques. The inclusion of samples from disarticulated and semi-articulated long bones introduced samples that could only be assigned broad age-at-death estimates.

The specific age-at-death assessments that had been recorded for each sample were noted where they were available. When the assemblage was considered as a whole, all of the samples could be classified into one of four broad age categories of neonate (foetal or less than one month), child (between one month and ten years old), juvenile (between eleven and nineteen years old), adult (over 20 years old). These categories represented the most precise age-at-death categorisation that could be applied to the mixed assemblage. Bones were placed within one of these categories based on either an age-at-death estimate that had been calculated through use of modern specific osteological aging techniques, or the size and state of epiphyseal union of discrete long bones. The benefit of this method was that it neutralised any biases that may have occurred as a result of different studies using diverse techniques of age estimation and categorisation.

The age categories used in the current study discerned between different types of immature individuals, but not between skeletons that had reached maturity. Whilst imprecise, this model suited the aims of the present study, as all of the age-related variations in bone diagenesis that have been posited describe differences between categories of younger specimens or dichotomies between sub-adult and adult remains (Jans *et al.* 2004; Turner-Walker 2008;

White 2009). The age-at-death classification system expounded above would be capable of capturing these potential changes whilst allowing for all samples to be included.

3.5.3.2 Sex

Bone remodelling rates vary between males and females, as these processes are thought to be partially regulated by sex-specific hormones such as testosterone and oestrogen (Junqueira *et al.* 1986). Sex differences in microstructural organisation are more subtle than those related to age (Khosla *et al.* 2006). Age-related sex-specific hormonal changes ensure that rates of bone remodelling differ more noticeably between males and females at certain ages (Junqueira *et al.* 1986; Khosla *et al.* 2006). These differences in remodelling rates may engender specific variation in the microstructural organisation of bone from different sexes, which could encourage variable levels of bone diagenesis (Bell *et al.* 1996; Jans *et al.* 2004; Turner-Walker 2008; 2012). The nuanced differences between the bone microstructures of males and females meant that it was unlikely that sex would have significantly affected levels of bone diagenesis. However, sex estimations for each skeletal sample were recorded where they were available to ensure that there were no sex-related differences in bone diagenesis and to explore whether diagenesis was dictated by microstructural organisation.

Most of the skeletons used in the current study had been allocated a sex estimation using the morphological characteristics of the pelvis, cranium and mandible where these bones were available (Phenice 1969; Ferembach *et al.* 1980; Katz & Suchey 1986; Krogman & Isçan 1988; Bass 1995; Buikstra & Ubelaker 1994; Schwarz 1995; Loth & Henneburg 1996; Brickley & McKinley 2004). These techniques were sometimes supplemented by metric measures such as diameters of the humeral, femoral and radial heads and distal radius, femoral bicondylar breadth and length of the glenoid cavity (Black 1978; Stewart 1979; Dittrick & Suchey 1986; Krogman & Isçan 1986; Berrizbeitia 1989; Chamberlain 1994). Metric analyses were more often used on disarticulated material that did not include sexually diagnostic features of the skull and pelvis.

Disarticulated long bones that did not retain sexually-diagnostic morphological features made up a considerable portion of the current study sample. A proportion of samples that could be subject to sex estimation demonstrated sexually ambiguous morphological features. These factors meant that only a fraction of samples could be allocated a sex estimate. Most studies displayed the certainty of non-indeterminate sex diagnoses using the standard system of Male

(M), Probable Male (M?), Indeterminate (??) Probable Female (F?) and Female (F). Biological sex of each specimen used in the current study was recorded initially using this method. However, the small number of samples that could be allocated a sex meant that the use of these four categories produced groupings that contained low numbers of remains. Therefore, remains that had been allocated an 'M' or 'M?' value were recategorised as 'M', those given 'F' or 'F?' values were reclassified as 'F' and specimens of indeterminate sex were excluded. The 'M' and 'F' categorisations were used to test differences between measures of diagenesis in bones from individuals of variable sex. However it had to be considered at the analysis stage that this method created a dichotomy in sex estimation that was likely to be inaccurate in reflecting the actual biological sex of each individual.

3.5.4 Chronological Concerns

3.5.4.1 Specific Phase

The main focus of the present study was the level of bacterial bioerosion observed between bone from Historical and Later Prehistoric contexts. However it was also pertinent to record the broad chronological phases that the Later Prehistoric bones could be assigned to: Neolithic (c.4000-2400 B.C.), Bronze Age (c.2400-700 B.C.) or Iron Age (c. 700 B.C.-A.D. 34). Some of the Later Prehistoric remains originated from sites that had not been dated using absolute techniques, and so this separation represented the highest level of resolution that could be applied to all samples. These boundaries are artificial and there has been debate over whether they provide any meaningful division of time and cultural change (Bradley & Hodder 1979; Rowley-Conwy 2007). However, whilst funerary ritual within each of these times periods is known to vary temporally and geographically, the cultural shifts attributable to these boundaries are conventionally thought to engender new ideologies and mortuary practices (Bradley & Hodder 1979; Rowley-Conwy 2007; Darvill 2010). It could be argued that any detectable changes in diagenesis that corresponded with the specific phase variable would support the suggestion that diagenetic change varies with funerary treatment. There would have to be some discussion of whether the nature of the change is likely to be related to cultural or natural shifts over time.

3.5.4.2 Archaeological Age

The lack of correlation between archaeological age and bone bioerosion of ancient remains is a defining characteristic of most studies of bone diagenesis (Hedges *et al.* 1995; Nielsen-Marsh & Hedges 2000; Hedges 2002; Jans *et al.* 2004; Nielsen-Marsh *et al.* 2007). However, the hypotheses that were to be tested relied upon the observation of higher levels of histological preservation within older bones. Any positive results might be questionable regarding whether internal preservation of archaeological bones allows for their survival over longer timescales. The absence of microbial tunnelling from fossil bones supports this assertion (Trueman & Martill 2002; Tuross 2002). Archaeological age of bone specimens represents a focal point of the hypotheses of this project, and so this variable was measured in terms of the Later Prehistoric/Historical dichotomy as well as specific archaeological phases (Neolithic, Bronze Age, Iron Age, Historical). This system of separation should provide a way of assessing the possibility that higher proportions of better preserved bones survived into the archaeological record from older sites.

3.5.5 Macroscopic Preservation

It was considered whether measure of macroscopic bone preservation should also be taken in order to investigate whether this factor had any bearing on bone diagenesis, as well as whether it provided useful complementary information in interpreting funerary treatment. The standardised method of recording surface preservation of archaeological remains was developed by Brickley & McKinley (2004). This system involved a visual assessment of cortical preservation, translated into an ordinal score from 0 to 5+, with 0 representing poor preservation and 5+ representing perfect preservation.

Most of the bones used in the current study had not been assessed using this system. The method of assessment was quick and simple, but locating the skeletons within the University of Sheffield's collections that had already been sampled for thin section analysis would have been time consuming. Some of the skeletons that were included within the thin section collection at the University of Sheffield no longer formed part of the gross skeletal assemblages, and so there was no guarantee that the microscopic preservation of every skeleton could be recorded. All studies that have investigated the relationship between bones diagenesis, particularly internal bone bioerosion, and macroscopic preservation of remains, have noted the lack of correlation between the two variables (Hedges *et al.* 1995; Hedges

2002; Jans *et al.* 2004). Therefore, a record of macroscopic preservation of each bone sample was not necessary for the present study.

3.5.6 Further Uncontrollable Variables

Most other variables that were suggested in the Background chapter as potential influencers of bodily putrefaction or bone diagenesis could not be controlled due to the nature of archaeological material. The influence of these factors could not be determined directly. If any of the following factors had a significant impact on bacterial bone bioerosion, their probable variation amongst the current study sample would ensure that the hypotheses set out in the previous chapter would not be supported.

Certain types of pathological conditions can leave lesions on the skeleton (Ortner 2003). Disorders such as periostitis (non-specific infection), syphilis, tuberculosis and leprosy represent those conditions that are most often detected in human skeletons (Ortner 2003). However, bacteria would only have affected the skeleton in the most severe of these cases (Ortner 2003). Most pathological conditions leave no skeletal record (Ortner 2003).

Signs of trauma are often found on skeletal remains, but these marks would only represent those wounds that penetrated far enough to have affected the bone (Boylston 2000; Ubelaker & Blau 2009). Types of penetrative trauma that may have affected bodily decomposition need not have marked the bones. There has been some suggestion that metric measures of long bones can be used to infer body mass at death (Auerbach & Ruff 2004). However, a large numbers of variables could affect long bone dimensions, and so their use as measures of body size are considered to be unreliable (Auerbach & Ruff). None of the samples used in the present study had been analysed using such methods and there was not sufficient time or resources available for them to be recorded specifically for the present study.

An endogenous model of bacterial bioerosion relies upon the consistency of destructive microbiota within an organism's gut. However, ratios of bacteria can vary within and between populations both temporally and geographically (Franks *et al.* 1998; Ley *et al.* 2008; Yatsunenko *et al.* 2012). The ubiquity of bacterial bioerosion within archaeological bones from various different species suggests that the bacteria responsible must be common to most vertebrates or that most types of vertebrate gut bacteria are capable of exploiting bone microstructure (Bell *et al.* 1996; Nicholson 1996; Davis 1997; Nielsen-Marsh *et al.* 2000; Jans *et al.* 2004; Nielsen-Marsh *et al.* 2007; Fernández-Jalvo *et al.* 2010). Species of bacteria are

adapted to breaking down different kinds of proteins (Child 1995a). The nature of an individual's gut microbiome would be partially controlled by diet. Stable isotope and osteological studies of bones and teeth can reveal some information about the diet of an individual during life. However, the majority of individuals sampled for the current study had not been subjected to such analyses.

Disease may also affect the nature and quantity of gut bacteria. There is currently no way of assessing the health of an individual's gastrointestinal microbiome from their archaeological remains. Factors that would have affected an individual's gut microbiome are likely to have varied amongst the diverse sample of Historical remains used in the current study. Any significant relationships between composition of an individual's microbiome and putrefactive bone bioerosion would be expected to falsify the hypotheses put forward in the previous chapter.

3.6 STATISTICAL ANALYSIS

3.6.1 Tests

All of the results from the diagenetic parameters and possible explanatory variables discussed above were recorded within a Microsoft Excel spreadsheet. Values from this spreadsheet were imported into IBM SPSS v.20 statistics programme. All charts and tables were produced within Microsoft Excel or IBM SPSS. All measurements consisted of ordinal or categorical variables. Therefore, only non-parametric tests were used in the statistical analysis. Results of statistical tests were considered significant if they reached the 95% confidence level ($p<0.05$). IBM SPSS displays p-values less than 0.0005 as 0.000. The same method of display had to be used throughout the Results chapter.

The distribution of variables was not equal across the study sample. It was possible that variation between two variables may have been affected by variation within other correlated observed or unobserved variables. Methods to determine the extent to which particular factors affected the diagenetic parameters would have to consider the complex effects of multiple variables. Regression models represented the best way to determine which factors had the largest influence on particular diagenetic parameters whilst controlling for the effects of all other variables. All of the dependent diagenetic variables included in the current study

were ordinal or binary. Ordinal and binary logistic regressions were used respectively for each type of data.

Both regression models produce two types of results: the influence of the explanatory variables on the dependent variable and the reliability of the regression equation in predicting outcomes within the dependent variable (Norušis 2012). These two types of results are intimately connected. However, the current study was concerned with the influence of explanatory variables rather than the ability to predict outcomes. The results from the tests of influence were the focus of the statistical analyses.

Ordinal regression does not determine the overall influence of explanatory variables, but the individual influence of each outcome (Norušis 2012). Each outcome within an explanatory variable is assigned a parameter estimate, which is the ordered log odds regression coefficient. This coefficient dictates the direction and size of the change within the dependent variable with each one unit movement of the explanatory variable, whilst each of all other explanatory variables remain constant. The size of the parameter estimate for each explanatory outcome and the associated sign (positive or negative) directly relate to the size and direction of an explanatory outcome's influence on the dependent variable. The parameter estimate quantifies the change in the dependent variable associated with movement to the outcome from its predecessor. The ordinal regression as performed in SPSS always takes the highest-numbered category within an explanatory variable as the reference point that constitutes the beginning of movement. Therefore the parameter estimate for the highest numbered outcome within an explanatory variable is always zero (Norušis 2012).

The next relevant figure is the Wald X^2. The Wald tests the true value of a parameter in explaining a dependent variable based on the sample estimate. The Wald X^2 tests the likelihood that the parameter estimate is equal to zero and that the associated shift between outcomes has no discernable effect on the dependent variable (Norušis 2012). The significance of the Wald X^2 value and the decision to reject the null hypothesis is determined by the accompanying p-value. The ordinal regression output produces two tests that reflect the predictive power of the model. The Model Fitting Information provides a X^2 comparison of the predictive power of the ordinal regression against a basic intercept model that does not consider specific predictor variables. If the ordinal regression model is useful, then it should have greater predictive power than the basic intercept and produce a significant X^2 value. The goodness-of-fit test produces a Pearson X^2 comparison between the values observed within the dataset and those predicted by the ordinal regression equation. A useful ordinal regression

model would produce values similar to those observed and generate an insignificant Pearson's X^2 result. The Nagelkerke Pseudo R-Squared value represents the proportion of variation in the dependent variable that is described by a particular regression model (Norušis 2012).

The construction of the ordinal regression relies on the proportional odds assumption, which is that all ordered logit coefficients (parameter estimates) are equal across levels of a particular outcome. The proportional odds assumption can be tested using the Test of Parallel Lines. This test uses a Pearson's X^2 analysis to determine whether the parameter estimates produced for the ordinal regression significantly deviate from an idealised model of equal proportional odds. A statistically significant X^2 value would indicate that a single ordinal regression equation was not appropriate for producing a predictive model for the dependent variable using the specific explanatory variables.

Binary logistic regression produces results that can be used to gauge the influence of particular explanatory variables on the binary dependent variable and the usefulness of the subsequent regression equation in predicting dependent variable outcomes. The binary logistic regression produces the log odds change in the dependent variable with a single unit change in the explanatory factor, whilst all other explanatory variables remain constant. This value is calculated for each outcome within an explanatory variable. This value is equivalent to the parameter estimate produced by ordinal regression, but in binary logistic regression it is referred to as Beta (B). The statistical significance of B is tested via the Wald X^2. Unlike ordinal regression, the Wald X^2 is also calculated for each variable as a whole where there are more than two outcomes.

The predictive power of binary logistic regression models is tested similarly to those produced by ordinal regression. The Omnibus Tests of Model Coefficients provides X^2comparisons of the binary logistic model and an intercept regression that does not consider explanatory variables. The predictive efficacy of the logistic regression model is also tested using a Hosmer & Lemeshow X^2, which compares observed results to those predicted by the model. The binary logistic regression also produces a Nagelkerke R-Squared value that states the proportion of variation in the dependent variable described by the model.

The regression models could not address all relevant question. Correlation and omnibus tests had to be employed to test associations between certain pairs of variables. These tests were also used to investigate relationships between subsamples of remains. Bivariate correlations between ordinal variables were tested using Spearman's rho correlation coefficients. These tests produce values that express the percentage of variation in one variable that is explained

by the other. This value is positive or negative depending on whether the relationship between the two variables is direct or inverse. The null hypothesis for this test is that the two variables are independent of one another. The significance value (p-value) expresses the likelihood that the correlation between the two variables occurred by chance.

Correlations between categorical variables were calculated using Pearson's X^2 analysis. This test compares the observed variation between two variables against an idealised model of expected values that would have occurred by random chance. The expected values represent the null hypothesis that the two variables are independent of one another. Pearson's X^2 test relies on the assumption that all expected counts will be greater than five. If any cells demonstrate expected counts of less than five, Pearson's X^2 test has to be discarded and Fisher's Exact Test employed instead. The significance value from Fisher's Exact Test expresses the same information as Pearson's X^2. When applied to low sample sizes, Pearson's X^2 has to be corrected using Yates' Continuity Correction.

Associations between categorical and ordinal variables were calculated using Mann-Whitney U and Kruskal-Wallis tests. Both of these techniques test the distribution of variation in a continuous or ordinal variables amongst categories defined by a categorical variable. The technique compares the differences within and between separate categories. The Mann-Whitney U test is applied to two categories and the Kruskal-Wallis to more than two. The null hypothesis is that the distribution of variation in the ordinal variable amongst the categories defined by the second variable is the same and that differences within categories are larger than the differences between them. The p-value expresses the likelihood that the variation between different categories could have occurred by chance.

Significant results from a Kruskal-Wallis test indicate that there is a difference in the distribution of values amongst the categories that have been defined, but does not identify the nature of this difference. A significant result would be produced if values from only one category differed from the rest or if values for all categories differed from each other equally. The factors that are responsible for the majority of significant variation can be discerned though a sequence of paired Mann-Whitney U tests.

The repeated application of correlation and omnibus tests, as well as those processes involved with regression models, raises the problem of multiplicity (Holm 1979). The confidence level of each statistical test, as well as each outcome within the regression models, was 95% ($p<0.05$). Each repeat test increased the likelihood of finding a significant effect by chance (the family-wise error rate), thereby raising the risk of Type I Error (rejection of the null hypothesis when it

is true). This problem can be neutralised using the Bonferroni Correction, which sets a corrected p-value for all tests. The desired family-wise error rate (0.05 for 95% confidence) is divided by the number of hypotheses tested (*i.e.* the number of tests that were carried out overall). This method ensures that the family-wise error rate does not exceed 0.05.

The Bonferroni Correction is a conservative method and increases the risk of Type II Error (acceptance of the null hypothesis when it is false), particularly when testing a large number of hypotheses (Holm 1979). A modified version of the Bonferroni correction called the Holm-Bonferroni method was used to account for multiplicity in the current study (Holm 1979). The Holm-Bonferroni method is still conservative, but ensures that the family-wise error rate remains below 0.05 whilst reducing Type II error. This method involves listing the p-values of all statistical tests from largest to smallest. The significant threshold for each test is calculated by the desired family-wise error rate (0.05) divided by the position of each p-value within the list (0.05/1, 0.05/2, 0.05/3…0.05/n).

The Holm-Bonferroni method produces a threshold within the list of p-values where the first null hypothesis is accepted. All p-values beyond this threshold will accept the null hypothesis. The increased rate of Type II error produced by the Holm-Bonferroni method meant that statistically insignificant results that lay close to this threshold were scrutinised further to determine whether they represented true relationships that had been dismissed in error.

The nature of regression in controlling for the effects of all variables meant that the inclusion of large numbers of explanatory variables was likely to distort the results from individual variables. It is difficult to determine whether correlated explanatory variables have an independent effect on the dependent parameter within a single regression model (Norušis 2012). Therefore regression models were run multiple times. Uninfluential explanatory variables were not carried forward into each repeat test. This methodology ensured that all of the independent significant explanatory variables were identified.

The distortive effect of multiple explanatory variables meant that the Holm-Bonferroni corrected p-values were too stringent to be used initially in determining which explanatory variables had influenced the dependent diagenetic parameter. Influential variables were included in further regression models when their p-values were under or close to 0.05. Repeated modelling of these influential variables eliminated the factors that had no independent influence on the dependent parameter. This protocol was repeated until all variables within a model were independently influential ($p<0.05$). At this stage the remaining p-values were assessed using the Holm-Bonferroni method to identify the significantly

influential explanatory variables. Regression models were run again with significant variables until all remaining variables demonstrated significant p-values under the Holm-Bonferroni method. If the regression models identified more than two significant influential variables, all significant variables were paired against each other within further regression models. Each comparison would determine the influence of an explanatory variable when controlling for the effect of each one of the others. If each explanatory variable maintained a significant influence on the dependent parameter then it was likely that they had all independently influenced the dependent variable.

3.6.2 Application of Statistical Tests to the Hypotheses

The first two hypotheses relating to the relationship between bacterial bioerosion and funerary treatment required a method of testing whether histological preservation of the Historical samples was consistently low. The usual way of testing for significant variation within a distribution is through comparison of observed values against a model of natural or random variation. Normal variation is usually defined as the model of natural variation within continuous data. Tests of normality such as a Kolmogorov-Smirnov test are used to determine whether a continuous parameter is significantly variable (Norušis 2012).

The primary measure of bioerosion used in the current study, Whole OHI, is an ordinal variable. This variable represents underlying continuous variation, and therefore natural variation was defined as a normal distribution. The hypotheses predicted that there would be a bias amongst the Historical samples towards the lowest Whole OHI scores. Such a bias would produce a normal distribution centred on Whole OHI scores of zero. This kind of normal distribution is referred to as half or folded normal. IBM SPSS statistics programme does not provide direct means of comparing an observed distribution against a half-normal model. In order to be able test whether Whole OHI data were half-normally distributed, all of the non-zero data points were replicated as negative numbers. This procedure produced a mirror image of the Whole OHI score distribution around zero. This mirrored distribution could be tested against a conventional normal model using a Kolmogorov-Smirnov Z-test (Norušis 2012).

The hypotheses stipulated that there should be no difference in distributions of Whole OHI scores amongst bones from separate Historical site assemblages. This hypothesis would be tested using a Kruskal-Wallis analysis of Whole OHI score distributions amongst separate

Historical site assemblages. An insignificant result would support the first hypothesis (Table 3.5). Statistical confirmation of the first and second hypotheses would indicate that all of the Historical site-specific distributions of Whole OHI scores conformed to a half-normal model.

Hypothesis	Statement	Result
1	If bacterial bone bioerosion is linked to funerary processes, bones recovered from Historical cemeteries will demonstrate consistent patterns of internal bacterial bioerosion.	Whole OHI Scores amongst the Historical assemblage demonstrate a half-normal distribution. Kruskal-Wallis test indicates no significant difference in OHI Scores between bones from different Historical sites.
2	If the nature of bacterial bone bioerosion is controlled by the extent to which early funerary processes dictate bodily putrefaction, all bones from Historical cemeteries will be characterised by high levels of internal bacterial decay.	Distributions of Whole OHI scores amongst the Historical bone assemblage and within separate Historical site assemblages are distributed half-normally.
3	If bacterial bone bioerosion can be used to distinguish between funerary rites, there will be a significant difference between the histological signatures of bone from the Later Prehistoric and Historical periods.	Phase (Later Prehistoric versus Historical) has a significant influence on histological preservation within an ordinal regression model. Bones from Later Prehistoric contexts demonstrate elevated and variable levels of histological preservation compared with the Historical remains.

Table 3.5: List of the statistical observations that could be taken to support the three main hypotheses relating to the relationship between bacterial bioerosion and funerary treatment.

The third hypothesis would be confirmed through the identification of Phase (Later Prehistoric/Historical) as a significantly influential explanatory variable within the ordinal regression model of Whole OHI scores. It was expected that this difference would manifest in an elevated and more variable Later Prehistoric distribution of Whole OHI scores. The expected relationships between the remaining diagenetic parameters and potential

explanatory factors could not be defined to the same standard. The factors that influenced these measures of diagenesis had to be determined through repeated regression models and omnibus tests.

4 MATERIALS

This chapter will provide brief overviews of each of the sites whose human remains were included in the current study. The majority of the human bone samples were taken for use in the Primary Analysis that directly addressed the research aims and hypotheses set out in the Methodology. A group of supplementary remains were also included to help improve the scope of funerary processes studied, as well as to address potential methodological issues. Summary tables of specimens are provided for certain sites where they provide important information regarding the osteological and contextual variation within an assemblage.

4.1 MATERIALS FOR THE PRIMARY ANALYSIS

Figure 4.1: Map of European Historical (Red Circles) and Later Prehistoric (Blue Crosses) sites used in the primary analysis.

Thin sections of human bone representing 301 individuals from across 25 Historical and Later Prehistoric European sites were examined for the Primary Analysis (Figure 4.1). One-hundred and-thirty-eight sections (46%) originated from the University of Sheffield's collections, whilst 163 (54%) were produced specifically for the current study. Each site overview provides a brief

history of excavation followed by archaeological evidence for the chronological dating and the nature of the funerary treatment. All of the sites included in the current study were excavated to modern archaeological standards between 1969 and 2004, and so the information regarding the positions and relationships between the skeletons was reliable and comparable. The chapter has been separated into the Historical and Later Prehistoric sites to provide an impression of the evidence for differences in funerary treatment between these two phases.

Most of the samples from the Historical assemblage, and some from the Later Prehistoric cohort, were not taken specifically for this study, but had been produced for previous research projects. Few of these thin sections had been analysed using the OHI, and none had been analysed using the full suite of methods that were used in the present study. Details regarding the sampling strategies used for these various projects are provided within each site-specific discussion.

4.1.1 Historical Site Assemblages

Bone from 208 individuals were analysed from across ten Historical archaeological sites (Table 4.1). Femora were sampled in 97% of cases. The rest of the samples consisted of other long bones including humeri, tibiae, radii and fibulae. The reasons for the inclusion of non-femoral thin sections are provided on a site-specific basis. The main aim of sampling from Historical assemblages was to ensure that there was representation from temporally and spatially disparate sites (Figure 4.2). It was expected that the signatures of diagenesis which related to funerary treatment amongst the Historical samples would be consistent regardless of variation in all other factors. Uniformity in levels of diagenesis within Historical archaeological bones that were widely dispersed around the country would provide compelling evidence for the link between bone diagenesis and funerary treatment. All of the Historical bones included in the current study originated from English sites. However, these sites were distributed widely across the country. The samples originated from sites that covered the whole range of possible Historical phases, from the Romano-British to Victorian periods.

Site	Location	Period	Number of Samples
All-Saints Fishergate Church	York, North Yorkshire	Roman/Medieval/Post-Medieval	39
Bantycock Gypsum Mine	Balderton, Derbyshire	Roman	7
Berinsfield	Berinsfield, Oxfordshire	Early Anglo-Saxon	20
Black Gate	Newcastle, Northumberland	Late Anglo-Saxon/Norman	25
Carver Street Methodist Chapel	Sheffield, South Yorkshire	Victorian	9
Cathedral Close	Exeter, Devon	Early Anglo-Saxon-Medieval	3
Royal Mint	East Smithfield, London	Medieval	38
St. Hilda's, Coronation Street	South Shields, Northumberland	Medieval-Victorian	29
St. Leonard's Hospital	Grantham, Lincolnshire	Medieval	10
St. Mary & St. Laurence Church	Bolsover, Derbyshire	Medieval-Victorian	28

Table 4.1: Catalogue of the Historical sites used in the primary analysis.

Figure 4.2: Map of the distribution of Historical sites used in the primary analysis.

4.1.1.1 All Saints Fishergate Church, The Barbican, York, North Yorkshire, U.K.

Figure 4.3: Map of the location of the All-Saint's Fishergate Church.

The remains of the All Saints Fishergate church are located underneath an area of the City of York that lies by the Barbican Leisure Centre at the corner of Kent Street and Fawcett Street (Figure 4.3). Skeletons were first exhumed from the site during trial excavations in 1987 and 2003. The majority of the skeletons were uncovered during commercial excavations by OnSite Archaeology Ltd. between 2007 and 2008, in advance of development. Thirty-one articulated skeletons were originally excavated during the 2003 trial excavations, followed by another 654 in 2007-2008. When combined with the disarticulated human remains that were found within unstratified sediment as and grave fills, the minimum number of individuals represent was determined to be 1136 (McIntyre & Bruce 2010).

Stratigraphic and artefact evidence suggested that there were three periods of burial. The earliest graves were determinable by their depth and their orientation (McIntyre & Bruce 2010). These earlier burials were orientated north-south rather than east-west (McIntyre 2010). The graves from this phase were linked stratigraphically with Roman-era ditches and Roman period finds were recovered from their fills (McIntyre & Bruce 2010). Seven skeletons were associated with the Roman phase of activity.

The next phase of activity was a burial ground associated with the medieval All Saints Fishergate church (McIntyre & Bruce 2010). The association between the burials and the church was apparent from the burials' east-west orientation and the way they respected the church's footprint (McIntyre 2010). Five-hundred-and-forty-seven individual skeletons were associated with this graveyard (McIntyre & Bruce 2010). Nineteen individual skeletons had been truncated by the church foundations (McIntyre & Bruce 2010: 34). The stratigraphic relationship between these burials and those left unmodified by the church, as well as similarities in burial styles, suggested that the truncated graves did not significantly predate the rest of the assemblage (McIntyre & Bruce 2010: 34). There was evidence that the stone foundations had cut through the remains of an earlier wooden building and it was likely that burials which predated the stone structure had been associated with an earlier timber church (McIntyre & Bruce 2010).

The first reference to the All-Saints Fishergate church dated to between 1091 and 1095 A.D. (McIntyre & Bruce 2010: 32). The remains of the timber structure probably represented a pre-Conquest church and suggested that the second phase of burial began in the late Anglo-Saxon period (McIntyre & Bruce 2010). Documentary evidence indicated that the church shared links with Whitby Abbey, and it was likely that burial at the site was halted by the Dissolution of the Monasteries in the 16th century A.D. (McIntyre & Bruce 2010: 32). One skeleton recovered from the apse of the church was radiocarbon dated to 1432-1488 Cal. A.D. (95% probability) (McIntyre personal communication 2012). This date supported the medieval use of the church and associated graveyard. Medieval pottery was found throughout the grave fills (McIntyre & Bruce 2010: 33). Graves had been frequently intercut, which suggested that they had not been afforded permanent markers (McIntyre & Bruce 2010: 33). The majority of the burials consisted of single graves, although a small proportion contained double burials, usually of an adult and child (McIntyre 2010). Only two of the medieval burials demonstrated evidence for coffin burial in the form of nails or stains in the ground (McIntyre & Bruce 2010: 32).

The third phase of burial activity consisted of ten mass graves that contained 113 articulated individual skeletons (McIntyre & Bruce 2010). The number of skeletons within each mass grave varied from four to nineteen individuals. These mass graves cut through the medieval deposits, but also respected some of the foundations of the stone church (McIntyre & Bruce 2010: 36). This patterning suggested that the graves had been constructed after the church fallen into partial ruin. The fills of the mass graves were all very similar, which indicated that they had been used over a short period of time (McIntyre & Bruce 2010: 36). The bodies had been organised into rows to ensure that the maximum number could be interred within each space.

The burials were defined by their lack of finds, which suggested that the bodies had been buried naked (McIntyre & Bruce 2010: 36). The lack of finds made it difficult to date the burials precisely. The demographic data obtained from the osteological analysis indicated that all of the skeletons were probably adult males (McIntyre 2010).

The mass graves had been cut by features relating to a 19th century cattle market (McIntyre & Bruce 2010). The evidence that the church had fallen into to ruin before the graves were dug inferred that burial took place a good time after the 16th century A.D. (McIntyre & Bruce 2010: 37). The use of mass graves is not a typical manner of disposal in Historical periods in Britain, except as a response to a mass fatality event where conventional burial rites are considered inappropriate or impractical (Wright *et al.* 2005). The heavy male bias of the skeletal assemblage was indicative of professions that were historically all-male, such as soldiers or sailors (Mays & Cox 2000). The best explanation for the archaeological and osteological data was that the mass graves were produced in 1644 during the siege of York by Parliamentary armed forces affiliated with Oliver Cromwell (McIntyre & Bruce 2010: 37). The idiosyncratic layout of the skeletons within the mass graves at All Saints Fishergate was identical to the organisation of remains within other mass graves associated with the English Civil War at Abingdon in Oxfordshire (McIntyre & Bruce 2010: 37).

Two discrete pits containing disarticulated human skeletal material were also discovered at the site. There were no finds associated with these contexts (McIntyre 2010). These pits included the bones of women and sub-adults, the types of remains that were absent from the mass graves (McIntyre 2010). The pits were interpreted as representing post-medieval reburial of disarticulated medieval deposits that had been disturbed by the digging of the mass graves (McIntyre & Bruce 2010). Disarticulated bones were also recovered from throughout the grave fills of all burial horizons. The sequence of deposition suggested that these bones represented the remains of medieval individuals that had been disturbed by later grave digging. It was possible that a small proportion of the unstratified disarticulated bones consisted of disturbed Roman skeletons (McIntyre 2010).

The anatomical articulation of the skeletal material from the York Barbican site suggested that all bodies had been buried intact soon after death. Charnel bone retrieved from most contexts was entirely disarticulated, and could be explained by later disturbance long after their initial deposition (McIntyre & Bruce 2010). The religiosity associated with the Roman inhumations could have been different to that associated with the later Christian skeletons, but it was likely that the Roman individuals had also been buried soon after death (Toynbee 1985). It was safe

to assume that the majority of individuals from the medieval Christian cemetery had been buried intact soon after death. It was difficult to infer what sort of rites were afforded to the individuals buried in the post-medieval mass graves, although none of these skeletons were disarticulated in a way that inferred delayed burial (McIntyre & Bruce 2010).

The sediment associated with all the phases of burial was a homogenous sandy clay (McIntyre personal communication 2010). There was no evidence for any previous water saturation at any of the burial depths. It was unlikely that these soils had retained water well enough to have produced frequent episodes of anoxia through waterlogging. The 2007 archaeological excavation of the York Barbican site was undertaken in one of the wettest summers ever recorded, but no burials became saturated as a result (McIntyre & Bruce 2010). There was no significant organic preservation or discolouration of burial sediments that may have been indicated previous environmental anoxia.

Human remains from the York Barbican site were sampled for thin section analysis by the author and Downey (2012) for use in the current study and a Masters research project. The thin sections were prepared using the method expounded in the Methodology chapter. Downey (2012) graded the York Barbican thin sections using the OHI. However the writer independently graded these sections to provide results for Downey to use in inter-observer tests. Downey did not record diagenetic features extraneous to microbial bioerosion and these features were recorded specifically for the current project.

Downey (2012) was not primarily concerned with the archaeological contexts of the bones. Therefore, samples were taken from the disarticulated material recovered from the discrete pits and the grave fills in order to limit damage to the research potential of the assemblage (Downey 2012). Downey (2012) sampled varied long bones from the left side of the body that could be broadly aged as child, juvenile or adult. All of Downey's (2012) femoral thin sections were included in the analysis for the current project. The precise provenance of the bones that were sampled could not be discerned, although their disarticulation suggested that it was likely that they all originated from the medieval phase of burial.

4.1.1.2 Bantycock Gypsum Mine, Balderton, Derbyshire, U.K.

The Bantycock opencast gypsum mine lies to the south of Balderton village, Nottinghamshire, England (Figure 4.4). Excavations of the site took place in 1999 in advance of the reopening of the mine. The excavation identified nine phases of activity based upon artefact typology,

ranging from the Early-Late pre-Roman (450-100 B.C.) Iron Age to the late Roman period (mid-4th century A.D. or later) (Pre-Construct Archaeology 2005). The site consisted of a low-status farmstead and settlement complex throughout the pre-Roman Iron Age and most of the Roman period (Pre-Construct Archaeology 2005). Towards the later Roman period (mid-4th century A.D.), evidence for occupation of the site steadily declined. A small inhumation cemetery was established sometime around or after the 4th century A.D (Pre-Construct Archaeology 2005).

Figure 4.4: Map of the location of the Bantycock Gypsum Mine.

The excavation recovered twenty-four sets of individual articulated inhumations and an additional six sets of disarticulated bones. The majority of the individual articulated remains were recovered from the later discrete cemetery, although single individuals had also been inhumed within the settlement throughout the Pre-Roman Iron Age and Romano-British phases. Radiocarbon dating of one of the skeletons confirmed that the cemetery was in use 120-340 Cal. A.D. (95% confidence) (Pre-Construct Archaeology 2005). The artefact evidence indicated that the cemetery probably belonged to the latter half of this range (Pre-Construct Archaeology 2005: 4). Most of the skeletons were recovered from within defined graves, although three had been deposited within ditches. Some of the graves demonstrated fittings

and furniture suggesting that the bodies had been inhumed within coffins (Pre-Construct Archaeology 2005: 53). The trussed attitude of one of the skeletons was suggestive of burial within a shroud (Keal 2005: 3). One of the female individuals had been placed within a stone-lined grave and was accompanied by the *in situ* skeleton of her unborn foetus (Keal 2005: 3). All of the adult remains had been buried in extended, supine positions, whilst the neonates were all recovered in flexed postures (Keal 2005). The foetus found *in situ* with the mother came from the discrete cemetery, whilst all other neonatal remains were associated with the settlement (Pre-Construct Archaeology 2005).

The chronology of the Bantycock site meant that it was unlikely the buried individuals had been subject to Christian funerary rituals (Toynbee 1985). Inhumation began to take over from cremation as the funerary rite of choice in Rome and throughout its provinces during the 2nd and 3rd centuries A.D., but there is some debate over whether this was due to the rise of Christianity (Toynbee 1985). Christian burials are normally orientated east-west (Parker Pearson 1999). All of the remains from the discrete cemetery were buried on a north-south orientation. The majority of the individuals retrieved from Bantycock were recovered in correct anatomical articulation and must have been buried soon after death. The few disarticulated remains consisted of only fragmented or single bones, and most likely represented charnel or remains from disturbed shallow graves (Pre-Construct Archaeology 2005). A small proportion of bodies from the Roman world were embalmed, although this rite was normally afforded to high status nobility, and is unlikely to have been performed at any of the individuals buried within the humble farmstead at Bantycock (Toynbee 1985; Papageorgopoulou *et al.* 2009).

The burial sediments at Bantycock consisted of brown loamy clay soils (Pre-Construct Archaeology 2005: 5). The density of heavy pure clay environments can sometimes produce an anoxic burial environment (Janaway 1996; Turner & Wiltshire 1999; Hollund *et al.* 2012). The coarseness of the clay soils present at Bantycock meant that they were likely to have been oxygenated and relatively free-draining (Pre-Construct Archaeology 2005). These burial soils should not have significantly interrupted bodily putrefaction (Janaway 1996). There was no evidence that any of the burial contexts had been previously waterlogged.

The Bantycock skeletal assemblage was originally sampled for thin section light microscopy by Lorraine White for use in her PhD thesis (White 2009). White's work was concentrated on bioerosion within neonatal remains and the strategy for sampling was based on optimising numbers of these samples. Infant skeletons were recovered from dispersed contexts across

the site and this strategy provided a good representation of bones from different contexts. White sampled femora from seven of the skeletons from the Bantycock assemblage (Table 4.2). All of the remains sampled had been recovered in articulation. Two of the infant bodies had been recovered from the same burial context and were interpreted as a double burial. The samples from Bantycock were friable and had to be consolidated through embedding in LR White Resin (ASCO Laboratories). White (2009) investigated the bacterial attack within these thin sections, but this investigation consisted of a qualitative rather than quantitative assessment of microstructural change. All of White's (2009) samples were reassessed using the techniques adopted by the present study.

Specimen No.	Age	Phase	Context
Sk 13	Young Adult	Late 4th Century	Cemetery
Sk 19	Neonate - 6-9 months	4th Century	Settlement
Sk 21	Neonate - 0-1 month	2nd Century	Settlement
Sk 22	Foetal - 38-39 weeks	Unphased	Pit
Sk 23	Neonate – 0-1 month	Unphased	Pit
Sk 26	Foetal	Late 4th Century	Cemetery
Sk 27	Foetal – 39-40 weeks	Unphased	Pit

Table 4.2: Catalogue of the samples taken from the Bantycock Roman human bone assemblage.

4.1.1.3 Berinsfield, Oxfordshire, U.K.

Figure 4.5: Map of the location of the Berinsfield Anglo-Saxon cemetery.

Berinsfield is a small village located near the confluence of the Thames and Thame rivers outside of Oxford, Oxfordshire, England (Figure 4.5). Burials were first discovered at the village in 1974 during a watching brief at the Wally Corner gravel pit. Excavations conducted between 1974-5 by the Oxford Archaeological Unit discovered a variety of archaeological features, including an Anglo-Saxon cemetery (Boyle *et al.* 1995). The cemetery consisted of 100 graves that contained 114 inhumation and four cremation deposits (Boyle *et al.* 1995) (Figure 4.6). Some individuals were represented by disarticulated and unphased skeletal elements from the grave fills.

No programme of absolute dating has been conducted on the skeletons from Berinsfield. The chronology of the site is based upon the typologies of the grave goods (Boyle *et al.* 1995). Few of the graves intercut one another. Graves that were devoid of material culture could not be assigned a precise date (Boyle *et al.* 1995). The typologies of the weapons and brooches recovered from the cemetery suggested that it was in use from the 5th to the 7th centuries A.D., within the early Anglo-Saxon period (Boyle *et al.* 1995: 76). It was assumed that the unphased graves belonged to this chronological range (Boyle *et al.* 1995).

The majority of the individuals buried at the Berinsfield cemetery were interred articulated in discrete graves in extended supine positions (Boyle *et al.* 1995). A small proportion of the skeletons had retained lightly flexed postures, although the consistent grave measurements across the site suggested that these positions represented attempts to fit tall individuals into graves of uniform dimensions (Boyle *et al.* 1995: 116). Multiple burials were recovered from seven of the Berinsfield graves. In all cases there was evidence that the grave had been purposefully opened and the primary skeleton disturbed to make way for the insertion of a new individual (Boyle *et al.* 1995: 119). The primary individuals from these multiple burials demonstrated variable levels of skeletal articulation. The demographic composition of the individuals from some of the multiple graves suggested that they were reused as familial burial plots (Boyle *et al.* 1995**:** 119). The stratigraphic relationship between three skeletons deposited in a single grave (grave 133) was complicated by evidence for the activity of scavenging foxes (Boyle *et al.* 1995: 119). However, this grave was the only one from the site that demonstrated evidence for carnivore activity (Boyle *et al.* 1995: 57). A further six graves from Berinsfield contained small numbers of extraneous human bones (Boyle *et al.* 1995: 119). The few fragmentary bones of extra individuals found within these deposits were likely to represent charnel material that had been encountered during grave cutting (Boyle *et al.* 1995: 119).

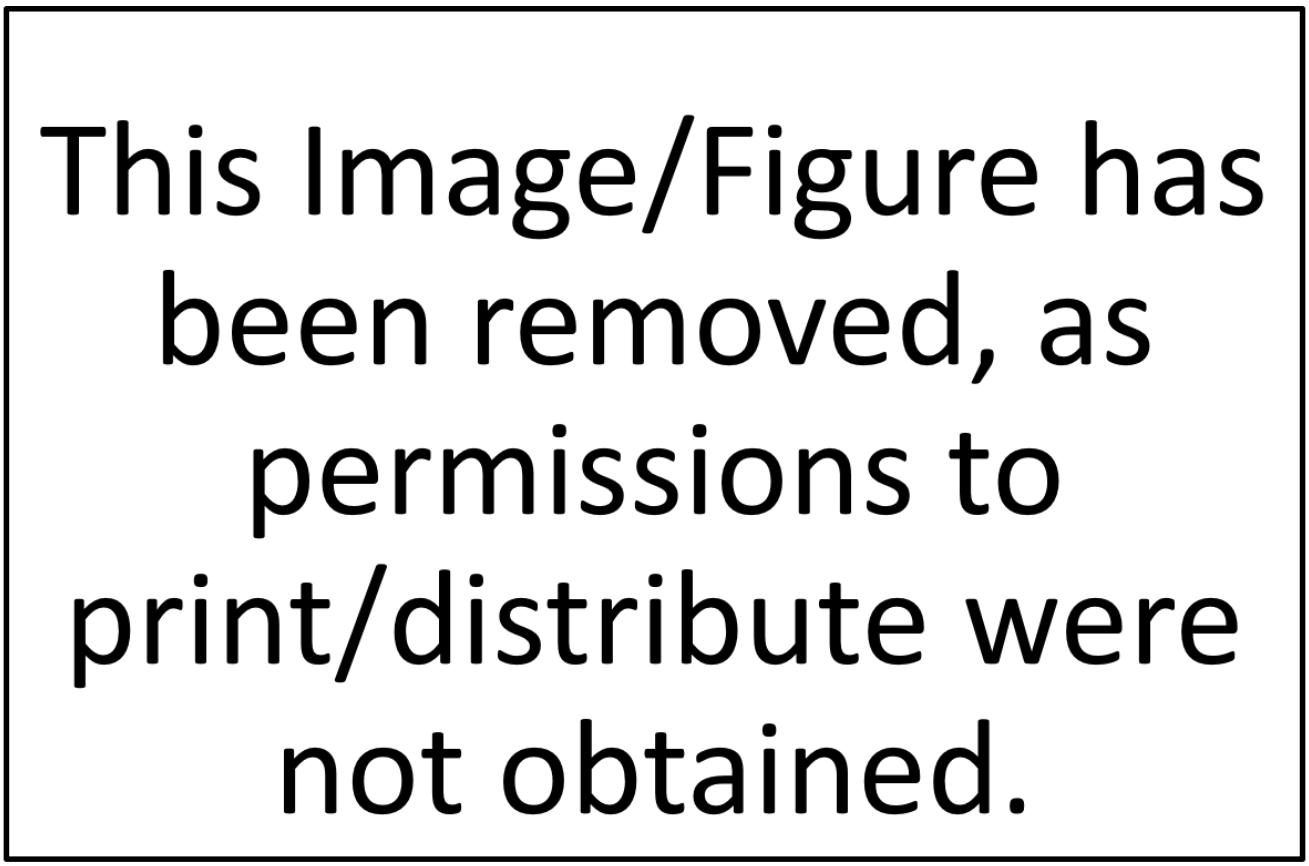

Figure 4.6: Plan of the Berinsfield Anglo-Saxon cemetery (Boyle et al. 1995: 9).

There was no evidence that any of the individuals recovered from Berinsfield had been buried within coffins (Boyle *et al.* 1995). Stains found within two graves (Grave 104 & 11) suggested that these contexts had been lined by charred logs (Boyle *et al.* 1995: 121). Four of the graves had been lined with stone slabs. This process may have represented an attempt to replicate the Roman cist burial, although the stone linings of the Berinsfield graves were too insubstantial to be classified as cists (Boyle *et al.* 1995: 121). It was unlikely that the Berinsfield graves produced an 'empty space' cist or coffin-like environment that differed from what was experienced by bodies in earthen graves. Organic material found beneath the body within Grave 102 suggested that it had originally been covered in a mat of woven rushes (Boyle *et al.* 1995: 121).

The individuals buried within the Berinsfield cemetery died before Christianity had been adopted by the Anglo-Saxons in the 7th century A.D (Lucy 2000). The pagan rites practised at Berinsfield were apparent within the orientation of the graves (mixture of N-S and E-W) and the presence of grave goods, which are normally absent from Early Christian Anglo-Saxon burials (Lucy 2000). Pagan Anglo-Saxon burial rites did not involve a long delay between death and burial (Lucy 2000). This notion is supported by the anatomical articulation of the Berinsfield skeletons. Those Berinsfield skeletons that had been disarticulated could be explained by later disturbance from grave digging (Boyle *et al.* 1995).

All of the burials from Berinsfield had been interred within free-draining gravel soils (Boyle *et al.* 1995: 8). The location of the cemetery on a river terrace suggested that the sediments may have been subject to annual recharge by rainfall and flooding. However, the free-draining soil would have ensured that the burial environment would not have experienced significant episodes of anoxia. There was no evidence that any of the graves had ever been waterlogged.

Bone of seventeen individuals from the Berinsfield Anglo-Saxon cemetery had already been sampled for thin section light microscopy by the author for use in an undergraduate dissertation project investigating spatial variation in bone diagenesis across a cemetery (Booth 2007). The seventeen individuals were selected using a stratified sampling technique aimed at obtaining a random distribution of bodies from different parts of the cemetery (Booth 2007) (Table 4.3). All of the skeletons sampled had been recovered in articulation. The left femur of each skeleton had been sampled consistently. None of the sampled skeletons had been recovered from stone-lined or wood-lined graves. The Berinsfield samples were friable and had to be embedded in LR White Resin before they could be sectioned (Booth 2007).

Femoral thin sections from an additional three Berinsfield individuals were identified within the collection held at the Department of Archaeology. There was only enough information accompanying these sections to identify the site, skeleton number and skeletal element. The original purpose of their sampling was unclear. Cross-reference with the skeletal report confirmed that these samples had been taken from articulated individuals. Some of the skeletons were accompanied by metallic grave goods, but it was unlikely that the presence of these items would have significantly interfered with putrefaction (Janaway 1996). The majority of grave goods were made of iron, which does not have bactericidal qualities (Janaway 1996).

The previous histological assessment of the Berinsfield thin sections did not use the OHI scale and had not recorded frequencies of other diagenetic features that were salient to the current project (Booth 2007). The same thin sections from Berinsfield were assessed by Lorraine White

(2009) but this assessment did not involve quantification of the bacterial attack using the OHI. All of the Berinsfield bone thin sections were assessed using the OHI along with the other methods that were adopted for the present study.

Specimen	Age Estimate	Sex Estimate
102	15-20	Female
126	Adult	Indeterminate
110	45+	Male
127	17-19	Indeterminate
134	45+	Female
14	8	-
152	17-19	Female
161	30-35	Male
164	35-40	Male
18	17-23	Female
22	30-35	Female
32	45+	Male
48	7	-
49	45+	Female
50	Adult	Female
53	30-35	Male
68	1.5	-
73	20-25	Female
77	35-40	Female
82	20-25	Male

Table 4.3: Catalogue of the samples from the Berinsfield Anglo-Saxon human assemblage.

4.1.1.4 Black Gate, Newcastle-upon-Tyne, Northumberland, U.K.

The Black Gate cemetery in Newcastle-upon-Tyne was discovered in 1977 during the excavation of two railway arches overlying the site of the city's medieval castle (Figure 4.7). This work was undertaken in advance of a programme of consolidation and landscaping by Newcastle City Council. The cemetery was excavated from 1977 until 1982, and then from 1990 to 1992 for Newcastle City Council (Nolan *et al.* 2010). Six-hundred-and-sixty burials were excavated, although subsequent osteological analysis determined that at least 679 individuals were represented (Nolan *et al.* 2010) (Figure 4.8). The majority of individuals were recovered in an extended supine position. The extra individuals were represented by disarticulated material from the grave fills. Evidence of intercutting within graves as well as the stratigraphic relationships between graves and other features suggested that all of the

disarticulated deposits had been produced during grave digging or construction (Nolan *et al.* 2010).

Figure 4.7: Map of the location of the Black Gate cemetery.

This Image/Figure has been removed, as permissions to print/distribute were not obtained.

Figure 4.8: Plan of the Black Gate site (Nolan et al. 2010: 153).

The typologies of shroud pins and coins found with some of the skeletons suggested that burial at the site began in the 8th century A.D, and continued through to the 10th century A.D. (Nolan *et al.* 2010: 157). Excavations were carried out in several discrete zones. The uncertainty regarding the relationship between these areas meant that phases could only be established locally (Nolan *et al.* 2010: 154). Burial at the site was interrupted by the documented construction of the Norman castle in A.D. 1080 (Nolan et al 2010: 157). A series of radiocarbon dates of the skeletons confirmed that the site was in use from the 8th century to the 13th Century A.D. (Nolan *et al.* 2010: 282). The rate of interment was reduced after the construction of the castle keep in A.D. 1168-1178 (Nolan *et al.* 2010: 254). The date and correct anatomical articulation of the skeletons meant that it could be assumed that the majority of remains had been buried intact soon after death.

The ubiquity of shroud pins within the earlier graves suggested that the majority of the Anglo-Saxon individuals were wrapped or clothed when they were buried (Nolan *et al.* 2010: 246). This interpretation was supported by the tight unstable position of skeletons as they lay *in situ* (Duday 2006; Nilsson Stutz 2006; Nolan *et al.* 2010). The Norman skeletons were more often buried within stone cists, whereas the preceding Anglo-Saxon skeletons were all recovered from plain earthen graves (Nolan *et al.* 2010: 217). Few of the stone cists contained paved floors and lids, therefore the Norman bodies that would have decomposed within earthen burial conditions. A fraction of graves demonstrated evidence for coffin interment (Nolan *et al.* 2010: 217). Timber coffins were identified by the presence of dark carbonised stains. One skeleton had been buried within a chest (Nolan *et al.* 2010: 217). The presence or absence of evidence for a coffin was not recorded for every grave.

The burial sediment consisted of boulder clay (Nolan *et al.* 2007: 155). Heavy clay sediments can sometimes promote localised anoxia, although this is unlikely to have occurred within the sediments at Black Gate, as the spaces in the clay produced by the occasional fluvio-glacial deposits would have ensured that the soil remained aerated and free-draining (Janaway 1996; Turner & Wiltshire 1999; Nolan *et al.* 2010; Hollund *et al.* 2012). It was unlikely that these soils would have retained water and encouraged sustained periods of anoxia through waterlogging. There was no substantial organic preservation at the site that might have been indicative of anoxia or waterlogging (Nolan *et al.* 2010).

Human remains from the Black Gate cemetery had been sampled for thin section analysis by two different projects. Femoral thin sections had been taken from three articulated individuals that were suspected of having suffered from Paget's disease (Ashford 1998; Pantzer 2004). The

thin sections were sampled in order to aid in the diagnosis of the disorder, as the rapid pathological bone formation associated with the disease produces characteristic patterns of lamellar bone within the internal microstructure (Bell & Jones 1991; Ashford 1998; Pantzer 2004). The precise cause of Paget's disease is unknown (Bell & Jones 1991; Aufderheide & Rodriguez-Martin 1998). The nature of the disease has led most researchers to reason that it must have a viral or genetic aetiology (Aufderheide & Rodriguez-Martin 1998). Paget's disease is not thought to be a product of bacterial infection and so its presence should not have affected the rate of bodily decomposition (Bell & Jones 1991; Aufderheide & Rodriguez-Martin 1998). However, the alterations to the microscopic and macroscopic bone structures caused by Paget's disease may have affected the logistics of diagenesis (Bell & Jones 1991). The presence of Paget's disease would have to be considered when discussing any variation in bone diagenesis amongst the Black Gate samples. The increased porosity of the Paget's samples rendered them fragile, and the bone had to be consolidated in LR White Resin before viable thin sections could be produced.

A further sixteen individuals from the Black Gate cemetery had been sampled for thin section microscopy by White (2009). Most of White's (2009) samples were taken from disarticulated skeletal elements recovered from graves and grave fills. All of the adult material sampled by White originated from femora, but two of the neonatal samples were taken from humeri (White 2009). Non-femoral disarticulated material was only sampled from discrete depositional contexts to reduce the risk of duplicate sampling of individuals (White 2009). White's (2009) assessment of the Black Gate thin sections did not include a quantification of bioerosion. All of the samples produced by White were reassessed for the current study using the techniques discussed in the Methodology. White (2009) embedded all of the Black Gate samples within LR White resin before thin sectioning.

A further five femora from the Black Gate cemetery were thin-sectioned as part of the current project in order to increase sample size (Table 4.4). All of the samples were taken from unphased disarticulated femoral fragments. Femora from different sides of the body were only sampled when they originated from dispersed contexts to ensure that the same individual was not sampled more than once. Femoral fragments from opposite sides of the body were compared based on states of epiphyseal fusion, shapes and sizes in order to assess whether they could have been antimeres. Any femora that could have been antimeres were not sampled.

Specimen	Skeletal Element	Age Estimation	Sex Estimation
BG 3215	Femur	Neonate	?
BG 442	Femur	20-29	Male
BG 464	Femur	30-49	Female
BG3191	Femur	36 weeks	?
BG3277	Femur	27 weeks	?
BG90 3207	Femur	< 1 month	?
BG92 3664	Femur	5 or 6	?
BG90 3285	Fibula	32 weeks	?
BG90 3204	Humerus	40 weeks	?
BG90 3166	Tibia	39 weeks	?
BG90 3830	Humerus	18 months	?
BG90 3184	Humerus	4 or 5	?
BG 90 3219	Femur	Adult	-
BG 90 614	Femur	30-39	Male
BG 90 481	Femur	40-49	Male
BG 90 548	Femur	45-54	Female
BG 90 8	Femur	45+	Male
BG 90 127	Femur	Adult	-
BG 90 3199	Femur	Neonate	-
BG 9092 3156(2)	Femur	Adult	-
BG9092 3257	Femur	Subadult	-
BG9092 3694	Femur	Subadult	-
BG9092 3156	Femur	Adult	-
BG9092 3257	Femur	Adult	-
BG90 2700	Femur	Child	-

Table 4.4: Catalogue of samples taken from the Black Gate human bone assemblage.

4.1.1.5 Carver Street Methodist Chapel, Sheffield, South Yorkshire, U.K.

The Carver Street Methodist chapel is located in the city centre of Sheffield, South Yorkshire (Figure 4.9). The graveyard of the chapel was excavated in 1999 after a watching brief had identified articulated skeletons within the proposed site of a beer cellar (ARCUS 2004). The subsequent three months of excavations recovered 101 articulated skeletons from 47 grave cuts, as well as disarticulated skeletal elements representing an additional 25-30 individuals (ARCUS 2004). The Carver Street Chapel was originally built on the outskirts of Sheffield between 1804 and 1805 (ARCUS 2004). The Sheffield City archive still holds the burial register for the cemetery. All of the skeletons were interred between 1806 and 1855 (ARCUS 2004: 27). The cemetery was closed in response to the 1855 Burial Grounds Act, which discontinued the use of urban cemeteries in Britain. Inscriptions on tombstones combined with the local death

records indicated that there was continuous burial in the Carver Street graveyard over this period (ARCUS 2004). The religiosity of the site and correct skeletal articulation of most of the bones meant that it could be assumed that the majority of the bodies had been inhumed immediately after death.

Figure 4.9: Map of the location of the Carver Street Methodist Chapel.

Many of the graves at Carver Street had been reused and disturbed several times. This disturbance had partially disarticulated some of the skeletons (ARCUS 2004: 14). Partial articulation of some of the disarticulated remains indicated that they had been disturbed before they had skeletonised (ARCUS 2004: 60). Disinterment of remains during putrefaction may have interfered with the burial environment in a way that upset the progression of decomposition and bone bioerosion (Janaway 1996; Turner & Wiltshire 1999; Breitmeier *et al.* 2005). The extent of the disarticulation in these skeletons suggested that they had been disturbed after putrefaction had run its course, but results from these samples would have to be monitored for atypical patterns of bacterial attack. The grave stones, coffin plates and documentary evidence indicated that that grave plots had been reused for members of the same family (ARCUS 2004: 26). All grave cuts demonstrated evidence for having been re-cut at

least once (ARCUS 2004: 69). Some of the grave cuts were quite deep, reaching three metres below the ground surface (ARCUS 2004: 60).

The period during which the skeletons at Carver Street were interred was characterised by coffin burial (Litten 1991; Cox 1998). It was likely that the majority of individuals buried within the Carver Street cemetery were originally interred within wooden coffins (ARCUS 2004). Remains of coffins and coffin furniture were identified throughout the archaeological investigations at the site (ARCUS 2004). Many of the skeletons demonstrated slumping indicative of movement due to the collapse of an underlying coffin (Roksandic 2002; ARCUS 2004: 15). One of the burials had been given additional protection of a brick vault (ARCUS 2004: 27). The presence or absence of coffins associated with particular skeletons could not be discerned from the site report. Evidence for coffins within certain graves had been noted, but the presence of multiple individuals within single grave cuts meant that the skeleton associated with each coffin was not always deducible (ARCUS 2004).

The burial medium that surrounded the majority of the skeletons from Carver Street consisted of silty clay (ARCUS 2004). This type of soil would not be expected to produce anoxic conditions in of itself, however the sediments at Carver Street were very moist and some of the graves were waterlogged (ARCUS 2004: 5). Two deep grave cuts had penetrated the natural bedrock (ARCUS 2004: 5). The remains found within these contexts still retained soft tissue and adipocere, whilst other graves contained liquefied soft tissue (ARCUS 2004: 9). Waterlogging had occurred as a result of a high water table as well as deep burial, and was probably responsible for the high occurrence of organic grave furniture (ARCUS 2004). The inundation of the bodies would have produced an anoxic environment that interrupted bodily decomposition. The cessation of decomposition promoted by waterlogged conditions was apparent in the presence of preserved soft tissue and adipocere (ARCUS 2004).

This interpretation was supported by the palaeoentomological analysis of one of the waterlogged Carver Street graves (ARCUS 2004: 71). The low representation of Coleopteran and Diptera species, which would usually thrive within an enclosed environment that contained a decomposing cadaver, suggested that an early environmental event had prevented their proliferation. The depths of the graves meant that it was possible that all of the bodies from Carver Street had been affected by waterlogging at some point during their decomposition, and so all of the samples taken from this site had to be recorded as having originated from anoxic deposits (ARCUS 2004). It was possible that the low temperatures and

hypoxia encouraged by deep burial also interfered with the decomposition of these remains (Rodriguez & Bass 1985; Janaway 2006; Dent *et al.* 2004; Campobasso *et al.* 2001; Vass 2011).

Ten individuals from the Carver Street Methodist Chapel were originally sampled for thin section light microscopy as part of a Master project that investigated the differential effects of coffin and shroud burial on macroscopic and microscopic preservation of human bone (Davidson 2010) (Table 4.5). Nine left femoral samples were chosen on the basis of obtaining a representative sample of coffin and shroud burials (Davidson 2010). Examination of the plan of the burials confirmed that skeletons had been sampled from diverse areas of the site, which suited the aims of the current project. It was unclear where the author of the original study obtained information regarding which remains had been subject to coffin and shroud burial (Davidson 2010).

All of the skeletons sampled originated from discrete grave cuts, rather than charnel from grave fills. However, some of these skeletons had been disturbed, and were recovered in varying stages of anatomical articulation (ARCUS 2004). Some of the partially-articulated remains may have been disturbed whilst they were still actively decomposing. Variations in bone bioerosion that corresponded with articulation would be investigated amongst the Carver Street samples to ascertain whether disturbance during decomposition had affected bone bioerosion. Collapse of graves due to coffin movement or disturbance had caused bones of several individuals to become intermingled (ARCUS 2004). Sampling had been focussed on the left femur to ensure there was no replication of individuals. The methodology of thin section preparation was analogous to the techniques used in the present study (Davidson 2010).

Specimen	Grave	Row	Age	Sex	State
Sk 1010	3	2	25-35	Male	Articulated
Sk 1044	4	2	Adult	Male	Disarticulated
Sk 1095	18	5	50-60	Male	Partially Articulated
Sk 1135	10	3	16-20	Female	Articulated
Sk 1215	45	7	45+	Male	Articulated
Sk 1264	32	6	Adult	Male	Partially Articulated
Sk 1140	16	4	Adult	Male	Articulated
Sk 1231	37	6	25-39	Male	Articulated
Sk 1229	34	6	Adult	Female	Disarticulated

Table 4.5: Catalogue of the samples taken from the Carver Street Methodist Chapel human bone assemblage.

4.1.1.6 Cathedral Close, Exeter, Devon, U.K.

Cathedral Close is located to the west of Exeter cathedral in Devon, England, U.K. (Figure 4.10). The excavations that yielded the assemblage of skeletons discussed here took place between 1971-6 and were conducted by Exeter Museum Archaeological Unit. These works were initiated in response to the demolition of the Saint Mary Major Parish church. There was evidence for a cemetery at this site from as early as the 5th Century A.D., at the location of a previous Roman forum (Henderson & Bidwell 1982; Allan *et al.* 1984). Two of six skeletons that were excavated from the Roman burial phase were radiocarbon dated to 397-650 Cal. A.D. (95% confidence) and 414-760 Cal. A.D. (95% confidence) (Allan *et al.* 1984: 386). These results, plus evidence from the finds and stratigraphy surrounding the burials, indicated that the earliest cemetery at the site (known as Cemetery I) was established during the post-Roman and early Anglo-Saxon periods (Allan *et al.* 1984: 389) (Figure 4.11).

Figure 4.10: Map of the location of Cathedral Close.

Burial at the site was probably continuous into the second phase of activity, known as Cemetery II (Allan *et al.* 1984: 391). The orientation of the graves of Cemetery II as well as the associated finds suggested that this phase represented an Anglo-Saxon burial ground that was

linked to a 7th Century Anglo-Saxon minster (Henderson & Bidwell 1982; Allan *et al.* 1984). The burials from the Cemetery III phase of burial were aligned with the remains of the late Anglo-Saxon/Norman minster church of St. Peter that had been built in the 10th Century A.D. to replace the Saxon minster (Henderson & Bidwell 1982; Allan *et al.* 1984). This church served as the cathedral church of Devon and Cornwall from A.D. 1050 until the consecration of the Norman cathedral in A.D. 1133 (Allan *et al.* 1984: 391). Burials associated with this church continued up until the late 12th century A.D. when the building was destroyed and incorporated into the new St. Mary Major parish church (Allan *et al.* 1984: 391). Burial within the graveyard of the St. Mary Major church continued up until the 17th century A.D. (Henderson & Bidwell 1982; Allan *et al.* 1984).

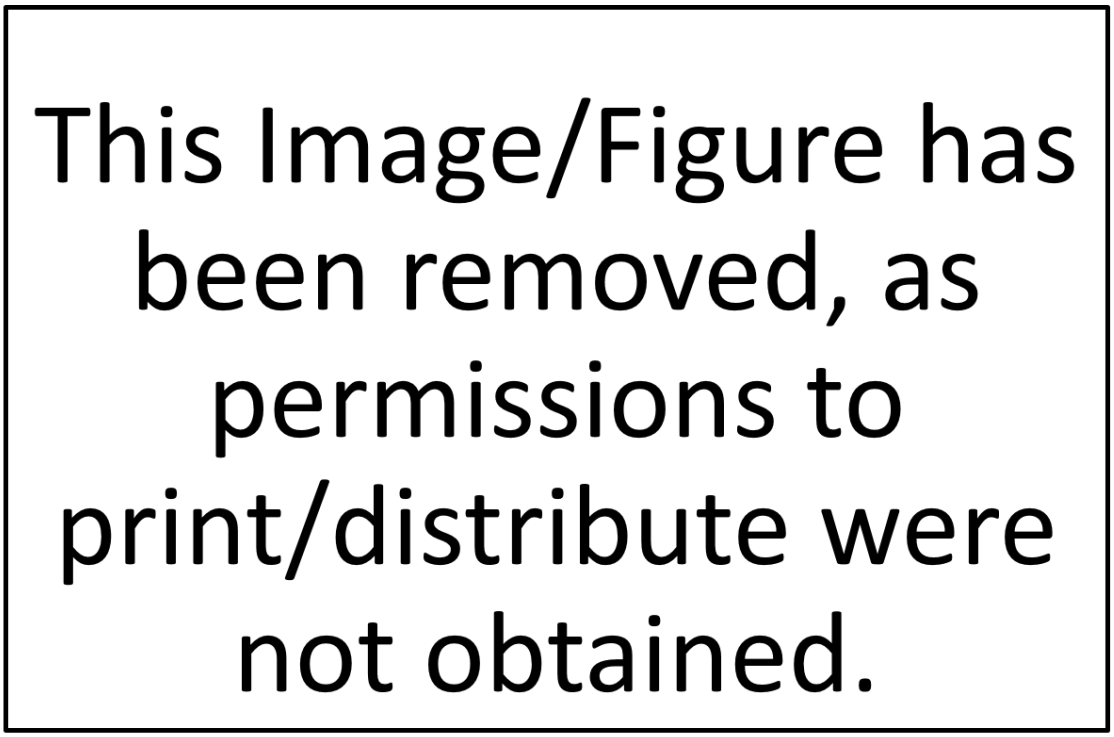

Figure 4.11: Plans of the various phases of cemeteries at Cathedral Close (Allen et al. 1984: 388, 390).

The excavations uncovered 272 articulated skeletons. Six of these burials originated from the Cemetery I phase and overlay the Roman forum (Henderson & Bidwell 1982; Allan *et al.* 1984). Skeletons representing 88 individuals had been cut by the medieval church of Saint Mary Major or the 12th century bell casting pit, and must have dated to the two successive Anglo-Saxon cemeteries (Henderson & Bidwell 1982; Allan *et al.* 1984). Fifty-three of these burials were reliably assigned to the earlier Cemetery II, based upon their differential alignments and

stratigraphy (Henderson & Bidwell 1982; Allan *et al.* 1984). Many of the burials associated with Cemetery III lay on the same orientation as the early medieval skeletons from the graveyard of St. Mary Major and consequently these two phases were difficult to distinguish from one another (Henderson & Bidwell 1982; Allan *et al.* 1984). Graves that belonged to Cemetery III were identified when they were cut by the medieval church (Henderson & Bidwell 1982; Allan *et al.* 1984). Burials in the south of the site were attributed to Cemetery II, as this area was occupied by buildings of the Kalendar brethren then the College of the Vicar's Choral from the beginning of the 13th century A.D. (Henderson & Bidwell 1982; Allan *et al.* 1984). Thirty-five burials could be associated with Cemetery III rather than St. Mary Major graveyard. The remainder of the skeletons could only be ascribed to a broad time range between the Anglo-Saxon and Medieval periods (Henderson & Bidwell 1982).

The majority of the skeletons excavated from the Cathedral Close site belonged to the Anglo-Saxon and early medieval phases of burial associated with the Saxon minster, the late Saxon church and the medieval Saint Mary Major parish church (Cemetery II & III) (Henderson & Bidwell 1982; Allan *et al.* 1984). The orientation of the burials from Cemetery I suggested that the site was a Christian burial ground from its inception (Allan *et al.* 1984: 386). The religiosity of the cemetery and the correct articulation of its skeletons meant that it could be assumed that most individuals had been buried intact soon after death.

Twenty-three of the Anglo-Saxon era burials demonstrated iron coffin nails or strapping (Henderson & Bidwell 1982; Allan *et al.* 1984). It was unclear as to whether there was evidence for coffin burial in the medieval periods, as the site report did not discuss the medieval remains in detail (Henderson & Bidwell 1982; Allan *et al.* 1984). It was likely that a proportion of the bodies interred within the graveyard of Saint Mary Major had been buried in coffins (Allan *et al.* 1984: 389). A small proportion of the Anglo-Saxon burials included a layer of charcoal deposited underneath the body (Allan *et al.* 1984: 389). Layers of charcoal appeared more frequently within graves that also demonstrated evidence for coffins (Allan *et al.* 1984: 389). Charcoal may have been used to absorb bodily fluids in an attempt to curtail bodily decomposition (Grainger *et al.* 2008). There have been no experimental tests of whether charcoal has this effect on a decomposing cadaver and it is unclear as to whether charcoal would have significantly affected putrefactive bone bioerosion. The site report did not provide a record of which individuals had been afforded these rites (Henderson & Bidwell 1982; Allan *et al.* 1984). The possibility that skeletons from Cathedral Close had originated from coffin and charcoal burials would have to be considered alongside the results from the histological analysis.

The skeletons from Cathedral Close had been buried within a sandy gravel environment that would have been free draining, and should not have encouraged anoxia through retention of water (Henderson & Bidwell 1982; Allan *et al.* 1984). There was no indications in the site reports that any of the graves had been waterlogged, and organic preservation at the site was poor (Henderson & Bidwell 1982; Allan *et al.* 1984). Only the metal fittings from coffins survived (Henderson & Bidwell 1982; Allan *et al.* 1984). These observations suggested that the graves were not exposed to frequent periods of anoxia that interfered with bodily decomposition

Three skeletons from the Cathedral Close assemblage were sampled for thin sections analysis by White (2009) (Table 4.6). It was not possible to determine which Anglo-Saxon cemetery phase these skeletons belonged to, although this lack of this knowledge was inconsequential to the aims of the current project. All of the thin sections had been taken the left femoral mid-shaft of articulated skeletons. The Cathedral Close samples were embedded in LR White Acrylic resin and mounted using Euparol. White (2009) did not assess samples using the OHI, therefore the three thin sections from Cathedral Close were reassessed using the techniques discussed in the Methodology.

Specimen	Age	Sex
Exe618	50+	F
Exe561	15-22	F
Exe635	25-35	F

Table 4.6: Catalogue of the samples of human remains taken from the Cathedral Close cemetery.

4.1.1.7 Royal Mint, East Smithfield, London, U.K.

The East Smithfield cemetery is located to the north-east of the Tower of London in the City of London and lies underneath the buildings that once formed part of the Royal Mint (Figure 4.12). Several excavations have been undertaken at the site since the 1970s. The human remains sampled for this project were uncovered in 1986-1988 during excavations by the Museum of London's Department of Greater London Archaeology (DGLA). Articulated skeletons representing 1012 individuals were recovered from the excavation area (Grainger *et al.* 2008).

The skeletons from the Royal Mint have not been subject to radiocarbon dating. Artefacts and documentary data could be used to split the skeletal assemblage into two phases (Grainger *et al.* 2008). The earliest phase of burial was linked to a cemetery and associated chapel (Holy

Trinity) that were founded to accommodate the dead that had accumulated as a result of the 1348-50 Black Death epidemic (Grainger *et al.* 2008). The cemetery may have been established to accept bodies from outlying parishes as well as the remains of local people (Grainger *et al.* 2008: 10). This area of the cemetery consisted of organised rows of single graves as well as mass burial trenches (Grainger *et al.* 2008). These burials could be split into two distinct eastern and western groupings. The dimensions of the East Smithfield cemetery corresponded with documented measurements of the burial ground associated with the Holy Trinity chapel (Grainger *et al.* 2008: 10). Coins and pottery dating to the 14th century A.D. were found throughout the sediments and in association with the skeletons (Grainger *et al.* 2008: 15).

Figure 4.12: Map of the location of the East Smithfield Royal Mint cemetery.

Mass grave trenches do not represent a conventional funerary practice in medieval Britain and usually occur as a practical response to mass fatality events (Wright *et al.* 2005). The use of ordered mass graves in medieval Britain was a specific protocol for dealing with the large volumes of Plague victims (Grainger *et al.* 2008: 19). The Black Death cemetery in East Smithfield was established in late A.D. 1348 or early 1349, and so the burials from the Black Death sections of the cemetery could be allocated a narrow range between A.D. 1348 and 1350 (Grainger *et al.* 2008). The Plague epidemic began to subside by A.D. 1350 and

supplementary cemeteries were no longer required (Grainger *et al.* 2008: 27). A small number of single graves were found intercutting the previous interments in the western part of the cemetery (Grainger *et al.* 2008). These graves probably related to intermittent outbreaks of the Plague that occurred throughout the 14th and 15th centuries A.D. (Grainger *et al.* 2008: 31).

There were no stratigraphic relationships between the single and trench graves. It was not certain whether trench graves were used from the cemetery's inception, or were initiated at a later stage when the volume of bodies began to increase (Grainger *et al.* 2008: 19). The ordered nature of the burials led the excavators to speculate that the single and trench graves had been dug at the same time and left open until they were filled (Grainger *et al.* 2008:19). The trench graves demonstrated soil slumping in their bases, which suggested that they been left open for an extended duration of time (Grainger *et al.* 2008: 19).

The trench graves were densely filled with stacks of up to five bodies (Grainger *et al.* 2008). The position of the skeletons suggested that the bodies had been carefully placed in an ordered fashion (Grainger *et al.* 2008: 19). Infant and juvenile bodies had been used to fill gaps between the adult individuals. Both single and multiple burials were represented. It was unlikely that these circumstances would have produced divergent patterns of decomposition and bone bioerosion (Mant 1987). The abundance of rotting cadavers within the mass graves would have produced a specific environment that was rich with putrefactive bacterial species. However, articulated skeletons from single graves can demonstrate the highest levels of putrefactive bioerosion (Nielsen-Marsh *et al.* 2000; Jans *et al.* 2004; Nielsen-Marsh *et al.* 2007). Mass graves could not have promoted a level of bone bioerosion that was any more severe than what can occur as a result of single burial. The differences in bone bioerosion between single and mass graves was scrutinised at the analysis stage.

The presence of corroded nails and organic stains suggested that some of the burials from the Black Death cemetery had been interred within coffins (Grainger *et al.* 2008: 13). Evidence for coffin burials were found within single and mass graves. The infrequent evidence for coffins suggested that coffin burial was not a common rite within the East Smithfield cemetery and that most individuals were buried either clothed or shrouded (Grainger *et al.* 2008). The site report contained a good record of those remains found with grave furniture. It was likely that traces of coffins had not survived into the archaeological record in every case. However, the bone samples taken from skeletons variably found with evidence for coffins were noted to investigate whether there were any differences in bone diagenesis with coffin burial.

King Edward III founded the Abbey of Saint Mary Graces at the site of the East Smithfield cemetery soon after the Black Death epidemic subsided (Grainger *et al.* 2008; Grainger & Phillpotts 2011). The Holy Trinity chapel was used as a church by the Cistercians until A.D. 1353 when it was incorporated into the abbey (Grainger *et al.* 2008; Grainger & Phillpotts 2011). A new church was built in association with the abbey around A.D. 1361 (Grainger & Phillpotts 2011). The second phase of burial at the East Smithfield site was associated with this church and the churchyard located to the east of the western Black Death cemetery (Figure 4.13). Four-hundred-and-forty single articulated skeletons were recovered from this phase. Burial at the site ceased after the Dissolution. All of the skeletons from the later phase dated to a period between A.D. 1360 and the mid-16th century A.D. (Grainger & Phillpotts 2011).

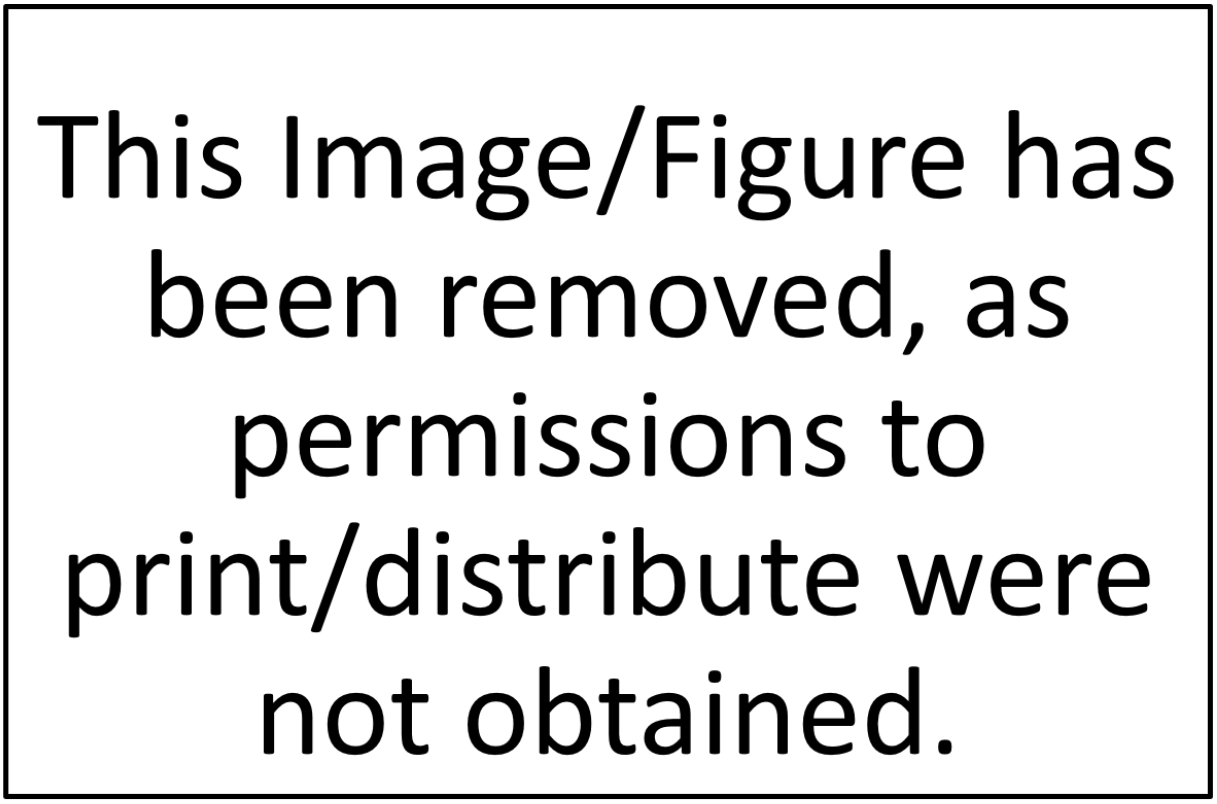

Figure 4.13: Plan of the East Smithfield Black Death and Abbey cemeteries (Grainger et al. 2008: 30).

The underlying pathogen associated with the Plague might have had some effect on the bodily decomposition and altered the way in which bones were bioeroded by putrefactive bacteria

(Mann *et al.* 1990; Vass 2011; Zhou & Bayard 2011; Fereira & Cunha 2013). A small number of the burials from the western Black Death cemetery were found in various stages of articulation without signs of grave disturbance. These bodies must have decomposed to some extent before they were interred, which inferred that there was a delay between their death and burial (Grainger *et al.* 2008). These burials may have represented bodies had not been discovered until a while after death or those remains that had been transported to the cemetery from elsewhere (Grainger *et al.* 2008: 19). The evidence that some of the graves had been left open for a time suggested that bodies may have decomposed within open graves for brief periods (Grainger *et al.* 2008: 19). Bodily decomposition in these examples may have been more akin to sub-aerial exposure than burial.

Some of the graves from both the Black Death and Abbey phases had been partially filled with charcoal (Grainger *et al.* 2008; Grainger & Phillpotts 2011). It was unclear whether these deposits represented the remains of planks, charring of a coffin or deliberate deposition of charcoal itself (Grainger *et al.* 2008: 20). In one case the charcoal included some domestic waste, which suggested that it had been deposited directly from a domestic context (Grainger *et al.* 2008: 20). Grainger *et al.* (2008: 21) hypothesised that charcoal may have been used to soak up fluid products of decomposition in order to slow the decomposition of individuals that had been transported long distances. It is unknown whether charcoal burial has this effect. Some of the charcoal burials originated from areas of the cemetery that were not associated with the Plague (Grainger & Phillpotts 2011: 104). Unfortunately, the presence and absence of charcoal was not recorded for each specific grave in the site reports (Grainger *et al.* 2008; Grainger & Phillpotts 2011).

Two of the coffined skeletons from the Abbey Church had been surrounded by quicklime (Grainger & Phillpotts 2011: 104). Application of both hydrated lime and quicklime retards bodily decomposition within the first six months through desiccation of the tissues (Aufderheide 2003; Kim *et al.* 2008; Schotsmans *et al.* 2012). Quicklime also has bactericidal properties (Aufderheide 2003; Kim *et al.* 2008). This process may have affected how the bone of these specimens had been bioeroded by putrefaction bacteria.

The burial sediments at the Royal Mint consisted of free-draining sandy gravel (Grainger *et al.* 2008: 5). These soils should not have encouraged episodes of anoxia via retention of water. There was no evidence that any of the graves had experienced sustained episodes of waterlogging, either in the form of organic preservation or sediment discolouration (Grainger *et al.* 2008; Grainger & Phillpotts 2011).

Specimen	Context	Age	Sex		Area	Grave Type	Coffin
1	5728	35-45	Male	Eastern	BD	Single	Present
2	9849	35-45	Male	Western	BD	Trench	Absent
3	11117	25-35	Female	Western	BD	Trench	Absent
4	9517	35-45	Male	Western	BD	Single	Present
5	12884	35-45	Male	Western	BD	Single	Absent
6	5265	25-35	Male	Eastern	BD	Trench	Absent
7	6388	Adult	Female	Western	BD	Single	Present
8	6398	25-35	Female	Western	BD	Single	Present
9	6509	35-45	Male	Eastern	BD	Single	Present
10	6602	15-25	Male	Eastern	BD	Single	Absent
11	7163	35-45	Female	Western	BD	Single	Present
12	8099	35-45	Male	Western	BD	Single	Present
13	13774	Adult	Male	Church	Abbey	Single	Present
14	13747	Adult	Male	Church	Abbey	Single	Absent
15	13530	Adult	Male	Church	Abbey	Single	Present
16	13666	35-45	Male	Church	Abbey	Single	Present
17	16122	45+	Female	Church	Abbey	Single	Absent
18	10348	45+	Male	Church	Abbey	Single	Absent
19	10070	45+	Male	Church	Abbey	Single	Absent
20	10250	5-15	Indeterminate	Church	Abbey	Single	Present
21	8126	Adult	Indeterminate	Western	BD	-	Absent
22	5859	35-45	Female	Eastern	BD	Trench	Absent
23	8210	45+	Female	Western	BD	Single	Absent
24	6545	Adult	Male	Eastern	BD	Single	Present
25	12774	45+	Female	Western	BD	Trench	Absent
26	6319	Unknown	Indeterminate	Western	BD	Trench	Absent
27	12691	35-45	Female	Western	BD	Trench	Absent
28	6383	35-45	Female	Western	BD	Single	Absent
29	8414	25-35	Female	Western	BD	Trench	Absent
30	8217	35-45	Female	Western	BD	Single	Present
31	12897	35-45	Male	Western	BD	Single	Present
32a	11606	35-45	Male	Western	BD	Trench	Absent
32b	10213	Adult	Indeterminate		BD	Trench	Unknown
33	10635	45+	Female	Church	Abbey	Single	Present
34	11997	Adult	Indeterminate	Church	BD	Single	Absent
35	10250	5-15	Unknown	Church	Abbey	Single	Present
36	10240	Adult	Female	Church	Abbey	Single	Present
37	14421	15-25	Female	Church	Abbey	Single	Present
38	10801	35-45	M	Church	Abbey	Single	Present

Table 4.7: Catalogue of the human bone samples taken from the East Smithfield Royal Mint cemetery.

The skeletons from the Royal Mint were sampled for thin section analysis by Tryzelaar (2003) as part of a 2003 Masters dissertation. Tryzelaar (2003) compared levels of bioerosion within bone from the Black Death and Abbey Church phases. All samples had been taken from femoral mid-shafts (Tryzelaar 2003). The samples had not been taken exclusively from one side of the body, as all bones sampled had been excavated as part of articulated skeletons (Tryzelaar 2003; Grainger *et al.* 2008). The Royal Mint sections were embedded within LR White resin but were otherwise prepared in a similar manner to the method outlined in the Methodology chapter.

Forty individuals from the Royal Mint site were selected for thin section analysis, although Tryzelaar only produced viable thin sections from 38 of these specimens (Table 4.7). Tryzelaar's strategy was to acquire a sample of remains that provided a good representation of the Black Death and Abbey Church phases of burial. The thin sections provided an adequate temporal and spatial representation of the site. This sampling was consistent with the objectives of the present study. The samples included almost equal proportions of coffined and non-coffined skeletons.

Tryzelaar (2003) did not use the OHI scores expressed in the methodologies put forward by Hedges *et al.* (1995) and Millard (2001) to assess bioerosion. White (2009) also assessed bioerosion within the same samples but not with use of the OHI. Further diagenetic features that were required for the present study were not recorded by either researcher (Tryzelaar 2003; White 2009) The diagenesis of the Royal Mint thin sections was reassessed for the present project using the techniques expounded in the Methodology chapter.

4.1.1.8 St. Hilda's Church, Coronation Street, South Shields, Northumberland, U.K.

St. Hilda's Church is located at Coronation Street in South Shields, Northumberland on the eastern bank of the River Tyne (Figure 4.14). The area that surrounds Saint Hilda's church has been occupied by religious buildings since A.D. 674, when a nunnery eponymous with the later church was established at the site (Gibson *et al.* 2009: 32). The original church was probably built in association with this nunnery (Gibson *et al.* 2009: 32).

The nunnery was built on the banks of a tidal inlet known as Mill Dam, which was filled in between the 17th and 18th centuries A.D. (Gibson *et al.* 2009: 32). It was likely that individuals were continuously inhumed in and around the church within a formalised churchyard (Gibson *et al.* 2009). The church that exists today was built in the 19th century A.D., although it is

probable that this structure stands on the same site as its predecessor (Gibson *et al.* 2009). By 1816, the graveyard had reached the full capacity of burials, and the ground level was artificially raised to facilitate more bodies (Gibson *et al.* 2009: 33). The cemetery was officially closed to new inhumations in 1856, although the burial records for the town suggested that interment continued until the 1860s (Gibson *et al.* 2009: 33).

Figure 4.14: Map of the location of the St. Hilda's church cemetery on Coronation Street, South Shields.

Skeletons from the cemetery formerly associated with Saint Hilda's church were uncovered during a watching brief and trial trench evaluation conducted by the Archaeological Services of the University of Durham (ASUD) in 2005 (Gibson *et al.* 2009). This evaluation was conducted in anticipation of modifications the sewerage system. One of the trenches uncovered only disarticulated human remains and broken gravestone fragments. An additional trench was dug at the projected southern edge of the graveyard. Fourteen grave cuts were identified at two metres below the ground surface. Four of these grave cuts were found to contain articulated skeletal remains. The finds associated with these burials dated them to the 18th and 19th centuries A.D. (Gibson *et al.* 2009). This evaluation trench was re-excavated by Oxford Archaeology North in 2006, with the purpose of excavating down to the natural features to remove all skeletal remains.

The Oxford Archaeology North excavations extended the original trenches to a maximum depth of 5.5m below ground level, excavating a total of 191 human burials; 168 discrete articulated individuals and 28 sets of disarticulated bones (Gibson *et al.* 2009). Disarticulated bones usually belong to formalised charnel deposits. Skeletons were excavated from two distinct burial horizons defined by the 1816 raising of the ground level (Gibson *et al.* 2009). The post-1816 skeletons were found between two metres and four metres below the modern surface within the raising material (Gibson *et al.* 2009:8). The earlier burial horizon was located between four-and-a-half and five-and-a-half metres below ground level (Gibson *et al.* 2009: 8). The graves of the lower horizon had been cut into grey silty clay fluvial deposits laid down by activity of the Mill Dam tidal inlet (Gibson *et al.* 2009: 8). The two burial horizons were separated by thirty centimetres of material that was used in the raising of the ground level. This level contained a small number of dispersed articulated and disarticulated skeletal deposits.

There was archaeological evidence for the presence of coffins from 177 of the Coronation Street burials (Gibson *et al.* 2009: 9). Evidence for coffins consisted of traces of decayed wood, stains in the surrounding soil, metal fittings and coffin plates. There was some partial survival of coffin upholstery in some contexts. Some of the coffins had probably left no archaeological trace. The majority of individuals from both phases of the cemetery had probably been buried within a coffin, as coffin burial had become ubiquitous for both rich and poor in Britain during the 18th and 19th centuries A.D. (Litten 1991). Formalised charnel deposits had been placed neatly on top of the coffins of intrusive interments (Gibson *et al.* 2009). Coffins from the lower burial horizon demonstrated higher levels of overall preservation than those from the upper horizon (Gibson *et al.* 2009).

The burials from the upper horizon could be broadly attributed to the period between the raising of the ground level and the termination of interment, 1816-c.1860 A.D. (Gibson *et al.* 2009). This interpretation was supported by the dates of the finds and grave furniture found throughout the sediment within graves (Gibson *et al.* 2009). The upper burial horizon also contained some residual medieval pottery within secondary deposits of industrial and domestic waste (Gibson *et al.* 2009). The skeletons situated in the lower burial horizon could have dated to any point between the graveyard's inception and the ground level raising event, from the early medieval period (5th- 10th century A.D.) to A.D. 1816 (Gibson *et al.* 2009: 7). The majority of skeletons recovered from the lower area were coffined (Gibson *et al.* 2009: 44). The single-break style and abundance of coffins recovered from the lower horizon suggested that most skeletons dated to the 18th century A.D. (Reeve & Adams 1993; Gibson *et al.* 2009).

The dating evidence, articulation of the skeletons and association of the burial ground with the church of Saint Hilda suggested that the majority of individuals had been interred intact soon after death.

The position of the organised charnel deposits and disturbed graves were noted throughout the excavation (Image 4.1). Patterns of articulation within charnelled skeletal elements suggested that some of the remains still retained some soft tissue when they were disturbed (Gibson *et al.* 2009). Some of the disarticulated remains from Coronation Street demonstrated evidence for having been disturbed before the body had decomposed (Gibson *et al.* 2009: 20). It was unlikely that disturbance of the remains at a late stage would have affected putrefactive bone bioerosion (Polson *et al.* 1985; Micozzi 1991; Janaway 1996; Jans *et al.* 2004; Adlam & Simmons 2007; De Jong *et al.* 2011). However, the early disturbance of remains may have to be considered an explanation for any significant variation in levels of diagenesis within the Coronation Street samples.

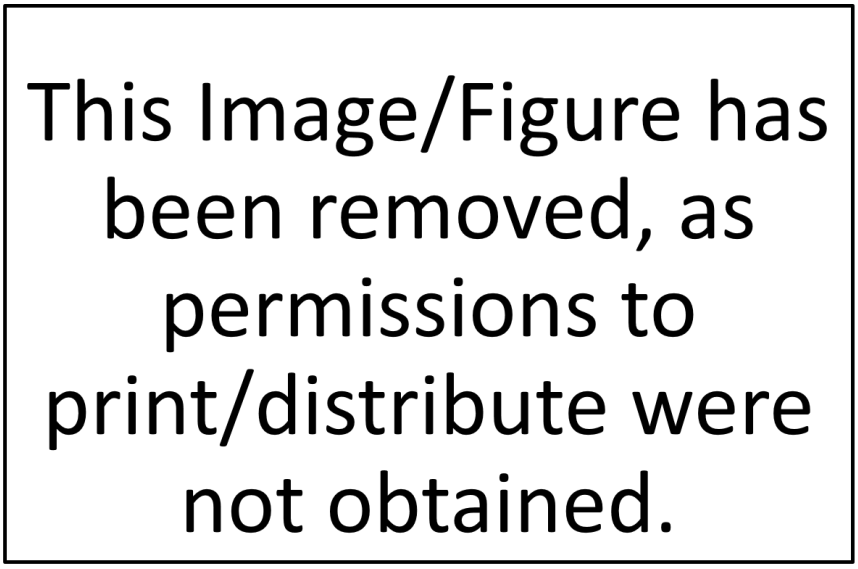

Image 4.1: Formal charnel deposit from the St. Hilda's Coronation Street cemetery (Gibson et al. 2009: Plate 9).

The material that was used in the raising of the graveyard that constituted the upper burial horizon consisted of a mixture of gravel, clay and industrial waste (Gibson *et al.* 2009: 8). The sediments of the upper horizon were described as free-draining and aerated (Gibson *et al.* 2009: 8). The silty clays that constituted the lower burial horizon had promoted the preservation of organic materials, which indicated that these sediments experienced periods of anoxia that had interrupted organic decomposition (Gibson *et al.* 2009: 8). The part of the

cemetery that was excavated lay directly adjacent to the site of the filled-in Mill Dam inlet (Gibson *et al.* 2009: 8). It was likely that the lower phase of the cemetery had been frequently waterlogged.

The deep burial of individuals from both phases may have also promoted anoxic or hypoxic burial environments (Rodriguez & Bass 1985; Janaway 1996; Dent *et al.* 2004; Vass 2011). Most skeletons interred within this cemetery would have decomposed over two metres below the ground surface where oxygen would have been limited (Rodriguez & Bass 1985; Dent *et al.* 2004). The low temperatures associated with deep burial in this environment may also have affected putrefaction (Rodriguez & Bass 1985; Janaway 1996; Campobasso *et al.* 2001; Dent *et al.* 2004; Breitmeier *et al.* 2005; Vass 2011). The high levels of organic preservation combined with the likelihood that many of the bodies interred at St. Hilda's decomposed within anoxic, hypoxic or cold conditions meant that all bones from the assemblage had to be considered as having originated from anoxic sediments that interfered with putrefaction and bacterial bioerosion.

Remains from the graveyard associated with Saint Hilda's church were sampled for thin section analysis for the present research project as well as for inclusion within a Masters research project (Downey 2012). The samples were prepared by the author and Downey (2012). Downey's (2012) project investigated variation in bone bioerosion with age-at-death. Downey (2012) sampled varied long bones from the left side of the body that could be broadly aged as child, juvenile and adult. Only left femoral thin sections were included in the current study to avoid replication of individuals. All of the samples could be cut without embedding. The samples were prepared using the techniques outlined in the Methodology chapter.

All of the bones sampled from the St Hilda graveyard originated from disarticulated charnel deposits (Table 4.8). The provenance of disarticulated samples was not apparent within the site report (Gibson *et al.* 2009). Some of the disarticulated material sampled had been recovered from the spoil heap or within unphased section of the site (Gibson *et al.* 2009). These bones did not have a secure context and could not be attributed to either burial horizon. It was not known whether the individuals sampled had been originally buried within coffins. The ubiquity of coffins within burials from both horizons combined with the 18th and 19th century penchant for coffined burial suggested that the majority of these bones probably originated from coffined bodies (Litten 1991).

Downey (2012) employed the OHI in their assessment of histological preservation in their bone thin sections. However, the writer conducted a parallel set of similar blind assessments to

provide data for inter-observer tests. Analysis of samples by the author was also required to record other measures of diagenesis. The OHI grades recorded by the author were used in then current study.

Specimen No.	Age
CS-301	Adult
CS-528	Adult
CS-535	Adult
CS-A	Adult
CS-C	Adult
CS-G	Adult
CS-H	Adult
CS-I	Adult
CS-J	Adult
CS-K	Adult
CS-K	Adult
CS-L	Juvenile
CS-B425	Adult
CS-B385a	Juvenile
CS-B385b	Adult
CS-527Bb	Adult
CS-527a	Neonate
CS-527d	Neonate
CS-49c	Neonate
CS-49b	Adult
CS-49a	Juvenile
CS-49d	Juvenile
CS-73Ab	Adult
CS-73Aa	Child
CS-73Ac	Child
CS-192	Child
CS-281a	Juvenile
CS-281b	Adult
CS-94a	Adult

Table 4.8: Catalogue of human remains sampled from the St. Hilda's Coronation Street assemblage.

4.1.1.9 St. Leonard's Hospital, London Road, Grantham, Lincolnshire, U.K.

Grantham is a small town in Lincolnshire, located a few miles outside of Nottingham. London Road is one of the main routes that runs through Grantham (Figure 4.15). The skeletal collection from London Road was excavated in 1991 as a result of rescue work undertaken by

Heritage Lincolnshire in advance of the construction of a service station (Heritage Lincolnshire 1992). Articulated remains representing 49 individuals were recovered from the site. Disarticulated charnel found within the grave fills raised the minimum number of individuals to over 50 (Boulter 1992).

The articulated individuals had been disturbed by later development and most survived in incomplete or fragmentary conditions (Boulter 1992). The graves had been filled with the same soil that was excavated in their construction, which meant that specific grave cuts were difficult to identify (Heritage Lincolnshire 1992: 6). A small proportion of remains from the south-east of the site demonstrated patterns of erosion consistent with exposure to heat or industrial chemicals and some had been stained by oil (Heritage Lincolnshire 1992: 6).

Figure 4.15: Map of the location of the cemetery of St. Leonard's Hospital, London Road, Grantham.

All of the skeletons lay in an east- west extended supine position (Heritage Lincolnshire 1992: 8) (Figure 4.16). The stratigraphy of the burials allowed for identification of a broad sequence of deposition. The earliest burials were directly adjacent to London Road and were cut by burials placed to the east (Heritage Lincolnshire 1992: 11). There was a clear development of the cemetery from west to east. The location of a grave in the cemetery reflected its

temporality (Heritage Lincolnshire 1992: 11). All of the skeletons were buried within two metres of the modern surface, although the depth of the original graves could not be established, as the historical ground level had not been preserved (Heritage Lincolnshire 1992: 11).

No religious buildings were recorded to have previously existed on the London Road site (Heritage Lincolnshire 1992: 4). However, there were references within the first Subsidy Roll of Lincolnshire to a medieval hospital within Grantham dedicated to Saint Leonard (Owen 1971; 1975; Heritage Lincolnshire 1992: 4). The hospital was first mentioned in records dating from the reign of Henry II (A.D. 1154-1189) and was probably founded sometime in the 12th century A.D. (Owen 1971; 1975). The lands of St. Leonard's hospital were acquired by the Crown during the Dissolution (Heritage Lincolnshire 1992: 4). The best estimate for the period of use of the cemetery was between the 12th and 16th centuries A.D. (Heritage Lincolnshire 1992: 4). The cemetery probably represented the farthest extent of the burial ground associated with St. Leonard's hospital (Heritage Lincolnshire 1992: 4).

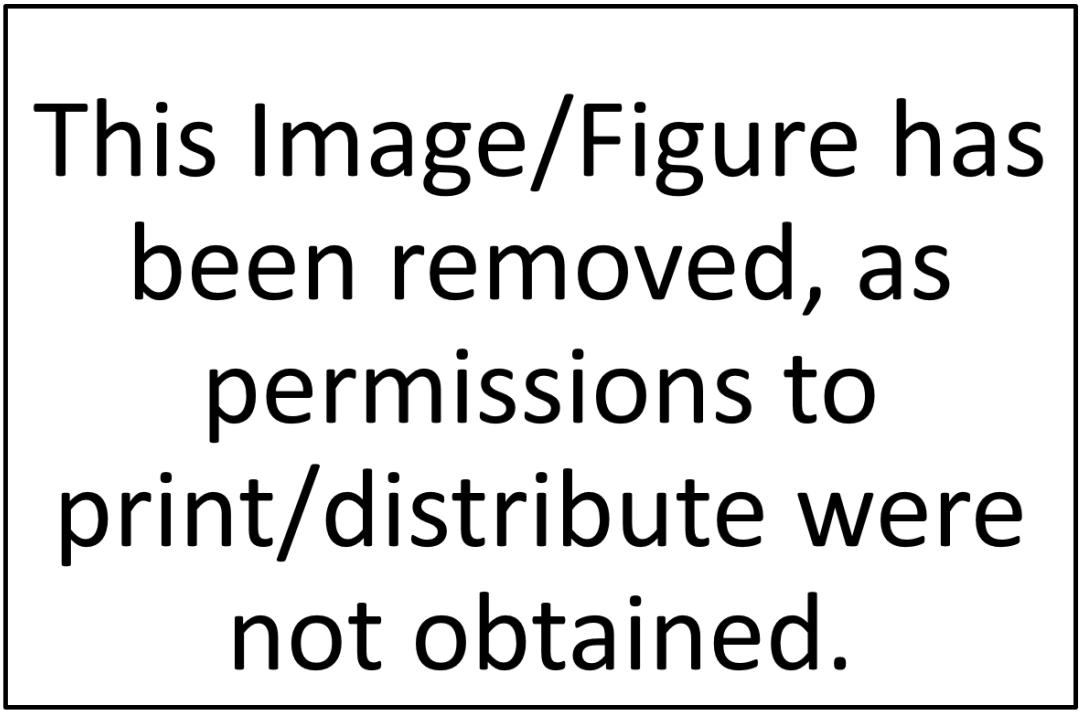

Figure 4.16: Plan of the burials from the cemetery of St. Leonard's Hospital in Grantham (Heritage Lincolnshire 1992: 11).

The hypothesis that the cemetery represented burial ground of the medieval Saint Leonard's hospital was supported by the archaeological evidence. The east-west orientation of the

bodies indicated a Christian burial rite (Heritage Lincolnshire 1992). Pottery sherds recovered throughout the excavation dated from the 5th and 14th century A.D. (Heritage Lincolnshire 1992: 12). There was no evidence for coffin burial, either in the form of preserved wood, stains or metal nails (Heritage Lincolnshire 1992). The unstable positions of some skeletons combined with presence of copper alloy pins suggested that bodies had been wrapped in shrouds (Heritage Lincolnshire 1992: 12). All of these features were consistent with medieval burials (Heritage Lincolnshire 1992). Two of the skeletons from London Road demonstrated pathological lesions indicative of leprosy (Boulter 1992).

The burial sediment consisted of brown silty sand (Heritage Lincolnshire 1992: 6). Soil of this type is likely to be coarse and free-draining (Janaway 1996). This type of sediment would not have caused the significant retention of water and subsequent episodes of anoxia through waterlogging (Janaway 1996; Dent *et al.* 2004; Carter *et al.* 2010). No evidence of waterlogging was recorded from any of the graves, and there were no significant levels of organic preservation (Heritage Lincolnshire 1992).

A selection of bones from the London Road cemetery were originally sampled for thin section analysis by Goodfield (1992) as part of an undergraduate dissertation investigating the relationship between bone microstructure and age at death (Goodfield 1992) (Table 4.9). These samples were also used in White's (2009) study. Goodfield produced histological thin sections from both the right and left femoral mid-shaft of ten individuals from Grantham in order to test for any differences between sides. Goodfield's (1992) strategy was based on obtaining samples that had been allocated variable age ranges and that were reasonably well-preserved. The main focus of this dissertation was the aging of adult remains and so the sampling excluded the remains of juveniles, children and infants. The skeletons that were sampled had been distributed across the site and were likely to reflect variable phases of use (Goodfield 1992).

Goodfield's (1992) samples included two of the three skeletons that demonstrated lesions consistent with leprosy (Heritage Lincolnshire 1992). It is uncertain whether pathological bacteria associated with chronic conditions such as leprosy are capable of biodegrading the internal bone microstructure in a way that is consistent with Hackett's non-Wedl MFD (Schultz 1993). It was possible that the increased *post mortem* bacterial load might have affected bodily decomposition (Polson *et al.* 1985; Mann *et al.* 1990; Vass 2011; Zhou & Bayard 2011; Fereira & Cunha 2013). The recognition of lesions consistent with leprosy on these particular skeletons meant that the potential effects of pathological bacteria on bone bioerosion could

be controlled. Other individuals represented by healthy skeletons from the London Road cemetery may have suffered from leprosy but had not yet developed the osteological expression of the disease (Aufderheide & Rodriguez-Martin 1998). The possibility that individuals represented within the Grantham samples suffered from leprosy would have to be considered when discussing any variation in diagenetic signatures of bone thin sections from this site.

Goodfield's (1992) study was not concerned with the measurement of microbial bioerosion. White (2009) did not make use of the OHI in her assessments of bone bioerosion. Goodfield (1992) prepared her sections differently to the methodology used in the current study. The thin sections from London Road were cut using an Exakt bench band saw and mounted onto slides using Flucromount fluid (BDH laboratory supplies). The refractive index of this substance is similar to glass. The bench band saw is not capable of cutting thin sections as precisely as the saw microtome used in the present project, and so the London Road thin sections were at least 150 microns thick (Goodfield 1992). Thicker thin sections can appear opaque. This opacity can obscure microscopic features (Schultz 1997). However, Goodfield (1992) had also thin-sectioned a number of modern femoral fragments using the same methods. Examination of the modern thin sections revealed that the increased thickness had not diminished or corrupted the microstructures appreciably, and that the thin sections from London Road were comparable to the thinner sections sampled using the saw microtome (Goodfield 1992). The left femoral thin sections of each London Road individual sampled by Goodfield was assessed using the OHI plus the techniques expounded in the Methodology chapter.

Specimen	Age	Sex	Pathology	Position in the Cemetery
10	30-40	Male	None	West
22	20-25	Female	None	West
34	20-40	Male	None	West
40	Adult	Male	Leprosy	West
42	35-45	Male	Leprosy	West
46	35-45	Male	None	East
56	30-40	Female	None	East
63	Adult	Female	None	West
67	45-50	Male	None	East
70	40-45	Male	None	East

Table 4.9: Catalogue of the specimens sampled from the St. Leonard's Hospital cemetery, Grantham.

4.1.1.10 St. Mary & Saint Laurence Church, Bolsover, Derbyshire, U.K.

The church of Saint Mary & Saint Laurence is located in Bolsover, a small town near Chesterfield, Derbyshire, England (Figure 4.17). Architectural features of the old parts of the church indicate that it was constructed no later than the 13th century A.D. (Foster 1992). The church was damaged by a fire in 1897, and subsequently renovated and rebuilt during the 19th and 20th centuries A.D. (Foster 1992). Skeletons were found underneath the church during emergency excavations in advance of building work (Kerr 1994). The excavation was conducted by the Creswell Heritage Trust between 1991 and 1992 and encompassed three areas within the church, as well as areas of the churchyard located directly outside the western walls and the main entrance (Foster 1992). A total of 70 articulated skeletons were excavated (Kerr 1994). Additional disarticulated material was recovered from grave fills and the surrounding soils. The disarticulation of this material suggested that all of the bodies had fully decomposed before they had been disturbed (Foster 1992).

Figure 4.17: Map of the location of the St. Mary & St. Laurence church and cemetery in Bolsover.

Four of the graves lay above the remains of a Norman knave, but were truncated by the foundations and walls of the 13th century tower (Foster 1992: 6). These observations suggested that the earliest burial activity at the site began in the Norman period before the 13th century

A.D. (Kerr 1994: 6). Four more graves had been truncated by 13th century features. The largest proportion of graves contained 18th and 19th century coffin fittings (Foster 1992: 6). Two graves located at the north of the church lay atop a 19th century storm water drain (Foster 1992; Economou 2003). The majority of the remains recovered from the north of the church consisted of the skeletons of children and infants (Foster 1992; Economou 2003) (Figure 4.18).

No absolute dating of the skeletons has been undertaken. Precise ages could not be assigned to any of the skeletons whose graves did not demonstrate stratigraphic relationships with dateable features. The majority of skeletons were allocated a broad age range of 13th-19th century A.D. (Foster 1992). The levels of skeletal articulation within discrete graves suggested that burial had occurred soon after death (Foster 1992). Disarticulated human bone recovered from the site had most likely accumulated through disturbance of decomposed bodies during grave digging or construction (Foster 1992).

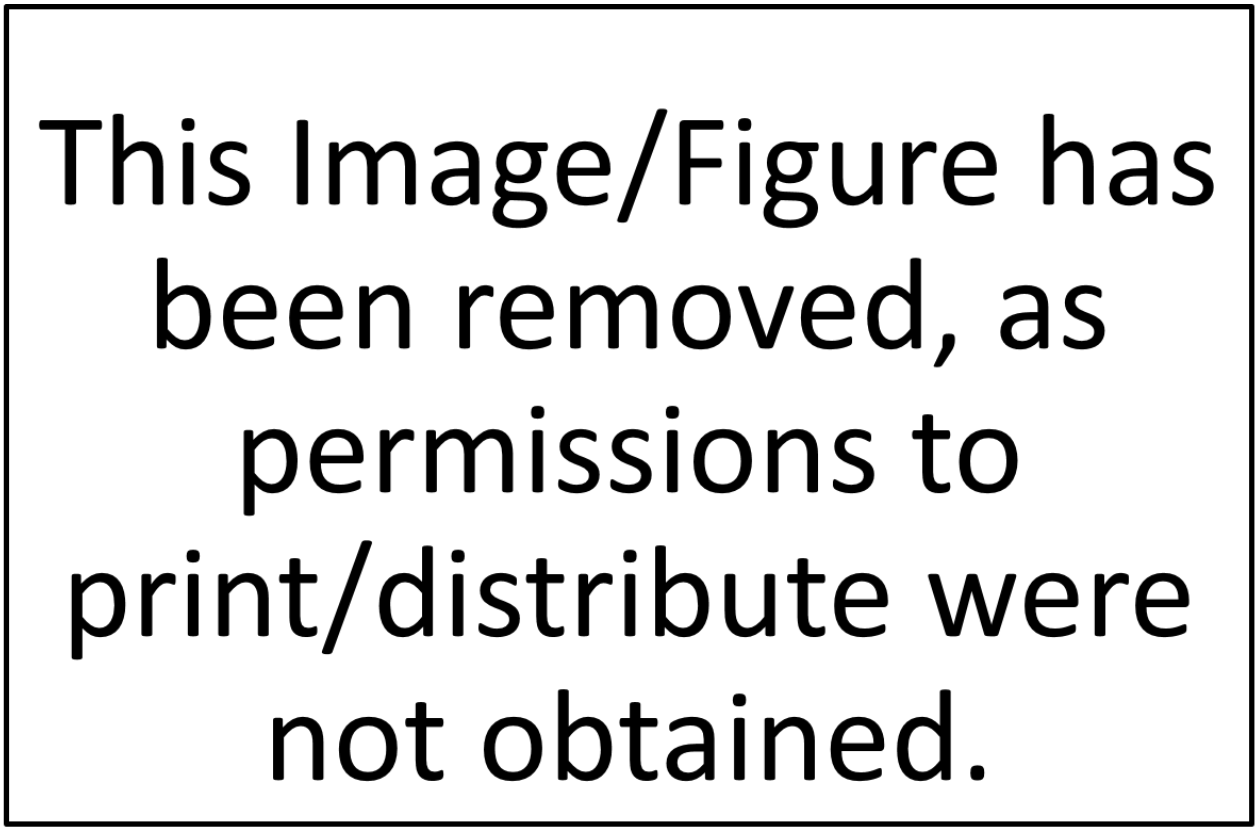

Figure 4.18: Plan of the burials excavated from St. Mary & St. Laurence church, Bolsover (Foster 1992: Figure 5).

Some of the skeletons recovered from underneath the nave of the church had been deposited within trench graves containing multiple individuals placed side-by-side (Economou 2003).

Multiple bodies would have decomposed within the trench graves, but the other circumstances of decomposition would have been very similar to those experienced by bodies within discrete cuts. There was no reason to believe that bodies within trench graves would have decomposed any differently to the single burials.

The sediments that surrounded the majority of skeletons recovered from the church consisted of clean re-worked natural clay (Foster 1992). The 19th century sediments included a large volume of construction debris that had formed as a result of the fire and major rebuilding works (Foster 1992). There was no reason to believe that any of the sediments had been waterlogged (Foster 1992). The clay soils would not have been entirely free-draining, but it was probable that they would not have retained water in a way that promoted sustained periods of anoxia (Foster 1992; Janaway 1996; Carter *et al.* 2010). Some of the skeletons were accompanied by remains of coffin furniture, although the site report did not indicate which graves included coffins (Foster 1992; Kerr 1994). Some of the 19th century burials contained traces of coffin timber (Foster 1992: 6). Organic preservation was not substantial and did not suggest previous sustained periods of anoxia.

A proportion of the skeletons excavated from the church of Saint Mary and Saint Laurence were originally sampled for thin sectioning by Economou as part of a Masters dissertation (Economou 2003). Economou's (2003) investigations were concerned with identifying age-related variations in bone bioerosion. Economou's slides were reused by White (2009) (Economou 2003). Economou sampled femora from seventeen of the articulated skeletons for thin section analysis (Economou 2003). Remains from across the cemetery had been sampled, including skeletons that were likely to have dated to diverse periods (Economou 2003). Economou's (2003) focus on neonatal remains meant that sampling was concentrated on the north side of the church where these skeletons were more prevalent (Foster 1992; Economou 2003). Femora had been sampled from alternating sides. However, all samples had been extracted from articulated individuals and there was no danger of replicate sampling of individuals. All of the thin sections had been mounted onto microscope slides using Euparal.

Neither Economou (2003) nor White (2009) quantified bone bioerosion in the Bolsover samples using the OHI. All of the Bolsover thin sections were reassessed for the present study using the methods described in the Methodology. A further twelve femora from the Bolsover site were sampled for the current project in order to increase the sample size (Table 4.10). All of the new bones that were sampled consisted of disarticulated charnel that had been

recovered from graves or grave fills. Thin sections were prepared and analysed using the methods adopted for the present study.

Specimen	Grave No.	Age	Sex	State	Area
Bol91-001	9	18-30 years	Indeterminable	Articulated	Tower
Bol91-002	20	~4 years	Indeterminable	Articulated	Tower
Bol91-003	19	20-40 years	Indeterminable	Articulated	South
Bol91-007	34	42 weeks	Indeterminable	Articulated	North
Bol91-008a	76	26 weeks	Indeterminable	Articulated	North
Bol91-008b	76	28 weeks	Indeterminable	Articulated	North
Bol91-009	79	38 weeks	Indeterminable	Articulated	North
Bol91-010	82	24 weeks	Indeterminable	Articulated	North
Bol91-011	85	39 weeks	Indeterminable	Articulated	North
Bol91-012	88	43 weeks	Indeterminable	Articulated	North
Bol91-017	133	40 weeks	Indeterminable	Articulated	North
Bol91-014	112	33 weeks	Indeterminable	Articulated	North
Bol91-018	135	4 years	Indeterminable	Articulated	North
Bol91-021	140	6 months	Indeterminable	Articulated	North
Bol91-028	186	39 weeks	Indeterminable	Articulated	Tower
Bol91-029	188	7 years	Indeterminable	Articulated	South
Bol-91-056	263	30 weeks	Indeterminable	Articulated	South
Bol-91-dis-7	Unknown	Adult	Unknown	Charnel	Unknown
Bol-91-dis-10	Unknown	Adult	Unknown	Charnel	Unknown
Bol91-dis-9	Unknown	Adult	Unknown	Charnel	Unknown
Bol91-dis-6	Unknown	Adult	Unknown	Charnel	Unknown
Bol91-dis-5	Unknown	Adult	Unknown	Charnel	Unknown
Bol91-dis-3	Unknown	Adult	Unknown	Charnel	Unknown
Bol91-dis-NN	Unknown	Adult	Unknown	Charnel	Unknown
Bol91-dis-11	Unknown	Adult	Unknown	Charnel	Unknown
Bol91-dis-4	Unknown	Juvenile	Unknown	Charnel	Unknown
Bol-91-dis-2	Unknown	Adult	Unknown	Charnel	Unknown
Bol-91-dis-2(2)	Unknown	Adult	Unknown	Charnel	Unknown
Bol-91-dis-10	Unknown	Adult	Unknown	Charnel	Unknown

Table 4.10: Catalogue of the skeletons sampled from the cemetery at St. Mary & St. Laurence Church, Bolsover.

4.1.2 Later Prehistoric Site Assemblages

Bone samples of 93 individuals from fifteen Later Prehistoric archaeological sites were sampled for use in the current study. The samples originated from all phases of the northern European Later Prehistoric periods; Neolithic (c.4000-2400 B.C.), Bronze Age (c. 2400-700B.C.) and Iron Age (c. 700 B.C.-A.D. 34). The few collections of Later Prehistoric human remains held at the

University of Sheffield consisted of articulated, disarticulated or partially disarticulated bone from five sites that dated to between the Neolithic and Iron Age. Human bone thin sections from three further Bronze Age sites were available within the University of Sheffield's collections. These bones had been sampled from outside institutions as part of the author's Masters dissertation (Booth 2008).

The rest of the Later Prehistoric remains were obtained from outside institutions. A strategy had been devised for identifying remains that would be useful for the current study. The primary sampling objective was to acquire optimal sample sizes that demonstrated evidence for variable treatment. The non-osteological variable that has been most often linked with changes in funerary practice in the British Later Prehistoric is phase (Darvill 2010). Therefore an effort was made to sample remains from a wide range of Neolithic, Bronze Age and Iron Age sites. It was also important to sample from Later Prehistoric assemblages that had been recovered from different parts of the UK in order to test for differences in bone diagenesis that could be attributable to variable environmental factors. The published and grey literature was studied to identify Later Prehistoric British sites that might provide useful samples. All of the sites that yielded high numbers of remains and that demonstrated evidence for variable treatment were entered into Microsoft Access database. The Access database included the following variables: location of the site, sex estimation, skeletal articulation, evidence for *post mortem* treatment, phase, direct radiocarbon date, indirect radiocarbon date (*i.e.* date taken from an accompanying artefact), position, putative location of the remains, date excavated and grave goods. These details provided enough information to prioritise remains that could be used to address the research questions (Background chapter page 3).

Later Prehistoric samples had to be collected through application to outside institutions for permission to perform destructive analysis. The destructiveness of microstructural analysis of bone combined with the obligation for museum curators to favour preservation meant that it was unlikely that every application to sample Later Prehistoric material would be accepted. The success of the current research project was dependent on retrieving a large number of Later Prehistoric samples. Application was made to sample as many remains as possible to ensure that positive responses would be high enough to ensure a good sample size. Sites that contained large numbers of remains were targeted preferentially, although these sites represented a minority of the total possible Later Prehistoric assemblages.

The majority of Later Prehistoric bones sampled for the current study consisted of fragments of femoral mid-shaft. A different long bone was chosen for analysis in a minority of cases. The

reasons for including a non-femoral long bone are provided below and were usually related to the need for larger sample sizes at sites where only limited numbers of individuals were represented by femora. The need to sample replicate elements combined with the low sample sizes of many of the Later Prehistoric collections meant that there could be no specific sampling strategy beyond taking all examples of a particular skeletal element.

Samples of bone from a Swedish Neolithic site were also included in the Later Prehistoric study sample. The Later Prehistoric date, evidence for variable treatment and temperate location associated with these remains meant that there was no methodological reason as to why they could not be included in the Primary Analysis. The addition of these remains increased the scope and size of the study sample. The inclusion of the Swedish bones also increased the diversity of the Later Prehistoric study sample, which increased its useful in determining whether early *post mortem* treatment had a primary influence on bone diagenesis (Table 4.11, Figure 4.19).

Site	Location	Period	Number of Samples
Beeston Tor CX	Wetton, Staffordshire	Neolithic	4
Bilham Farm	Brodsworth, South Yorkshire	Iron Age	2
Bradley Fen	Whittlesey, Cambridgeshire	Bronze Age	3
Carsington Pasture Cave	Brassington, Derbyshire	Neolithic/Iron Age	18
Cladh Hallan	South Uist, Outer Hebrides	Bronze Age	5
Cnip Headland	Isle of Lewis, Outer Hebrides	Bronze Age	7
Danebury Hillfort	Middle Wallop, Hampshire	Iron Age	18
Frälsegården	Falbygden, Sweden	Neolithic	10
Hornish Point	South Uist, Outer Hebrides	Iron Age	1
Langwell Cist	Strath Oykel, Scotland	Bronze Age	1
Neat's Court	Queensborough, Kent	Bronze Age	7
South Dumpton Down	Broadstairs, Kent	Bronze Age/Iron Age	6
Suddern Farm	Middle Wallop, Hampshire	Iron Age	2
Whitwell Quarry	Bolsover, Derbyshire	Neolithic	5
Windmill Fields	Ingleby Barwick, County Durham	Bronze Age	4

Table 4.11: Catalogue of the Later Prehistoric sites whose assemblages were used in the current study.

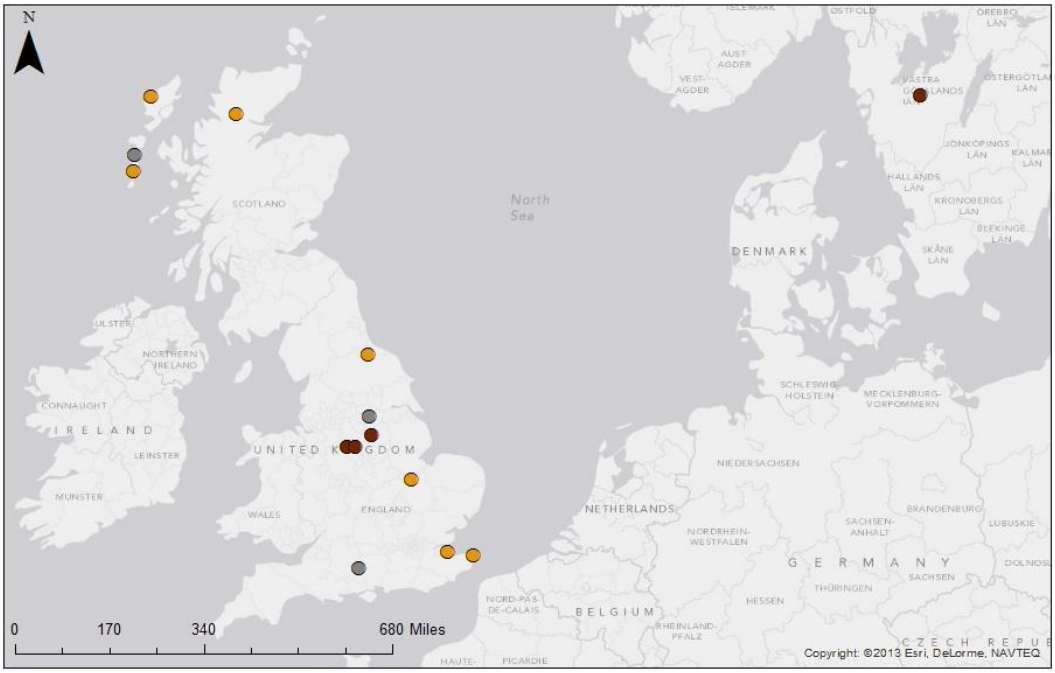

Figure 4.19: Map of the location of the Later Prehistoric sites whose remains were used in this study. The different colours refer to the specific phase that remains originated from predominantly, brown=Neolithic, gold=Bronze Age, grey=Iron Age.

4.1.2.1 Beeston Tor CX, Wetton, Staffordshire, U.K.

The Beeston Tor cave, otherwise known as St. Bertram's cave, is located next to the northern bank of the Manifold River, near the village of Wetton in Staffordshire (Figure 4.20). The human remains included in the present project were found within Cave CX, a previously unexplored opening towards the top of Beeston Tor Crag (Papakonstantinou 2009: 75). The cave entrance had been recorded by the Trent and Peak Archaeological Trust and the Royal Commission on the Historical Monuments of England (RCHME) as part of an archaeological survey. Human remains were found within the chamber by an amateur caver. Unauthorised excavations had revealed a sedimentological sequence of brown cave soils and calcite cemented cave surface as well as an assemblage of disarticulated and comingled human and animal bone (Papakonstantinou 2009: 76). The chamber was systematically excavated by Andrew Chamberlain and archaeologists from the University of Sheffield in 2009 (Papakonstantinou 2009).

Figure 4.20: Map of the location of Beeston Tor CX cave.

The aim of the 2009 excavations was to gain information on the ancient cave usage and produce recommendations for conservation of the site. The spoil of the unauthorised excavations consisted of dark brown humic soil and mottled red-brown silt with numerous inclusions of cave breccia and limestone clasts (Papakonstantinou 2009: 75). A small area of ground outside of the cave entrance was also excavated. The sediments outside the cave consisted of a brown humic soil that demonstrated extensive root development intense bioturbation by burrowing animals (Papakonstantinou 2009: 75). Inside the cave, a 120 centimetre redeposited horizon followed the western wall to its northern extremity (Papakonstantinou 2009: 75). This cut had been filled by a more gravelly form of the humic topsoil that had found outside the cave. This deposit was interpreted as representing a lead miner's trench (Papakonstantinou 2009). This trench overlay a pale brown silt containing faunal remains. This deposit was overlain at the northern extremity of the cave by a pale grey-brown silt with inclusions of breccia and limestone clasts (Papakonstantinou 2009: 75).

Three-hundred-and-thirty-eight disarticulated and comingled human bone fragments and 31 teeth were recovered from the cave (Papakonstantinou 2009: 77). The repetition of elements suggested that these remains represented at least eight separate individuals of variable ages (Papakonstantinou 2009: 77). Interment of human remains within caves has been practised

intermittently within most Historical and Prehistoric periods in Britain (Chamberlain 2006). However, cave burials of multiple individuals are most frequently associated with Later Prehistoric periods, particularly the earlier to middle Neolithic (Barnatt & Edmonds 2002; Chamberlain 1996; Darvill 2010). The excavation of the Beeston Tor CX deposits produced finds of chert and flint tools, a fragment of bronze wire and sherds of pottery (Papakonstantinou 2009: 75). The earliest pottery was dated typologically to the Neolithic. Two of the human bones produced radiocarbon dates of 3800-3650 Cal. B.C. and 2800-2500 Cal. B.C. placing them within the early and late Neolithic respectively (Papakonstantinou 2009). The lack of overlap between these two dates suggested that Neolithic deposition of remains within the cave was long-lived and that the Beeston Tor CX assemblage represented multiple episodes of interment over hundreds of years (Papakonstantinou 2009).

Over half of the human remains were excavated out of the humic soil and red silt sediment that had been disturbed during the unauthorised excavations. The remainder of the human bones had been recovered from the topsoil at the cave entrance (Papakonstantinou 2009). Three-per-cent demonstrated evidence for modification by carnivores or rodents (Papakonstantinou 2009: 80). Only three of these bones showed coincident evidence for natural weathering suggestive of sub-aerial exposure (Papakonstantinou 2009: 80). An unspecified larger number of human remains demonstrated evidence for root etching (Papakonstantinou 2009: 79). The evidence for extensive root action both within and outside of the cave suggested that this damage could have occurred whilst the bones were buried in the humic cave sediments (Papakonstantinou 2009). Several of the human bone fragments had been covered by concretions of flowstone (Papakonstantinou 2009).

Cut marks were identified on the cortical surface of an infant tibia. The position of the cut marks corresponded with specific muscle attachments, and suggested that the intention was to deflesh (Papakonstantinou 2009: 82). Levels of fragmentation amongst the assemblage were low when compared with the number of bones (Papakonstantinou 2009). The morphology of breaks suggested that they had occurred when the bone was dry (Wheatley 2008; Wieberg & Wescott 2008; Papakonstantinou 2009). Three of the adult femora demonstrated *peri mortem* spiral fractures (Wheatley 2008; Wieberg & Wescott 2008; Papakonstantinou 2009).

The smaller bones, such as those from the hands and feet, were underrepresented amongst the Beeston Tor CX human assemblage (Papakonstantinou 2009: 82). A lack of bones from the hands and feet is often taken to be indicative of prior decomposition of bodies elsewhere, as

these skeletal elements are amongst the first to disarticulate and are most commonly lost when a body is transported from a primary context (Mays 2008). However, there was also an underrepresentation of smaller bones whose articulation usually persists during decomposition, such as vertebrae (Papakonstantinou 2009: 82). The low representation of the smaller skeletal elements at Beeston Tor CX was most likely to have occurred as a result of differential preservation of skeletal elements by size as well as excavation bias (Papakonstantinou 2009: 82). The evidence from the skeletal part representation and cortical erosion of the bones inferred that intact or mostly intact bodies were deposited and had decomposed within Beeston Tor CX (Papakonstantinou 2009). These remains had been disarticulated and comingled by subsequent manipulation and disturbance.

The disturbance of the human remains made it difficult to determine the environmental conditions of their initial decomposition. The lack of anatomical relationships between the buried bones suggested that bodies had decomposed on the cave floor and the bones were incorporated into the sediments at a later stage. It was likely that all of the human bodies deposited within Beeston Tor CX had decomposed within an open cave environment. There was no evidence that the cave flooded regularly and so it was unlikely that waterlogging frequently promoted anaerobic decomposition (Papakonstantinou 2009). There was no evidence that the silts and humic soils that eventually contained the human bone assemblage were intrinsically anoxic, The accumulations of flowstone observed on some of the bones supported the suggestion that the bodies had originally decomposed on the cave floor and that bones had remained on the surface for a significant time before they were incorporated into the sediments (Papakonstantinou 2009).

The Beeston Tor CX assemblage was transported to the University of Sheffield Department of Archaeology, and so all of the bones from the site were available for sampling. Only left femora were sampled in order to avoid the risk of sampling the same individual multiple times (Table 4.12). The assemblage included four identifiable left femora. All of these specimens were sampled and analysed using the established methodology. All of the samples could be cut on the saw microtome without embedding.

Specimen	Age
219	Adult
145	2-3 years
280	Neonate
36	Older Adult

Table 4.12: Catalogue of the remains sampled for this study from the Beeston Tor cave assemblage.

4.1.2.2 Bradley Fen, Whittlesey, Cambridgeshire, U.K.

Figure 4.21: Map of the location of Bradley Fen.

Bradley Fen is located in the south-east of the Flag Fen basin, to the west of the town of Whittlesey in Cambridgeshire (Figure 4.21). The site was excavated in 2001 by the Cambridge Archaeological Unit (CAU) in advance of quarrying (Knight 2000; Appleby 2005). The main archaeological features consisted of a Bronze Age field system, an associated settlement and a collection of burnt mounds (Appleby 2005). The burnt mounds were associated with deposits of metal artefacts at the edge of the fen (Appleby 2005). The settlement and field system had been established on a higher natural terrace and were demarcated from the burnt mounds area by a north-south linear feature. The settlement consisted of a number of roundhouses as well as some four-post structures, interpreted as storage facilities (Appleby 2005). Numerous watering holes and ponds had been dug within the settlement and field systems to allow for a fresh water supply when the water table was low (Knight 2000).

There was archaeological evidence for prehistoric activity at Bradley Fen from the Neolithic to the Middle Iron Age (Appleby 2005: 18). Neolithic Peterborough ware pottery was recovered from within pits located around the site. Many of the rest of the features were assigned

phases through their relationship with an episode of peat formation that was dated to 2300-1510 cal. B.C. (Appleby 2005: 18). The field systems dated to the Middle Bronze Age. Settlement activity in the form of the four-post structures began in the Late Bronze Age (Appleby 2005). This activity was accompanied by further metalwork deposits at the fen edge including a substantial Bronze Age hoard (Appleby 2005: 18). This phase of activity could be dated to the Late Bronze Age by the typology of the metalwork (Appleby 2005: 18). Material associated with one of the roundhouses from the settlement yielded Late Bronze Age radiocarbon dates of 900-800 cal. B.C (Appleby 2005: 19). A scatter of pottery sherds that dated to the Late Bronze Age, Early Iron Age and Middle Iron Age were found overlying earlier features further up the slope. The gradual movement of activity away from the fen edge was interpreted as representing a relocation to higher ground in response to the Flag Fen basin becoming increasingly wet over time (Appleby 2005: 19).

Disarticulated and articulated human remains amounting to at least five individuals were recovered from a variety of contexts around the Bradley Fen site (Appleby 2005; Knight personal communication 2008) (Figure 4.22). The disarticulated remains of an adult female (Sk. 901) were recovered from the banks of a filled-in pond. The distribution of skeletal elements suggested that the body had been deposited whole within the pond and subsequent water movement had distributed the bone along the bank (Knight personal communication 2008). An articulated skeleton of an older adult male (Sk. 573) was discovered within a partially-backfilled post hole associated with one of the four post structures from the settlement (Knight 2000). The post hole was 0.4m-0.7m in diameter and 0.3-0.4m deep. The body was supine and had been contorted into a tightly flexed posture in order for it to fit in the post hole (Knight 2008, personal communication) (Image 4.2). Part of the backfill of the post hole that lay underneath the skeleton consisted of metalworking slag (Appleby 2005).

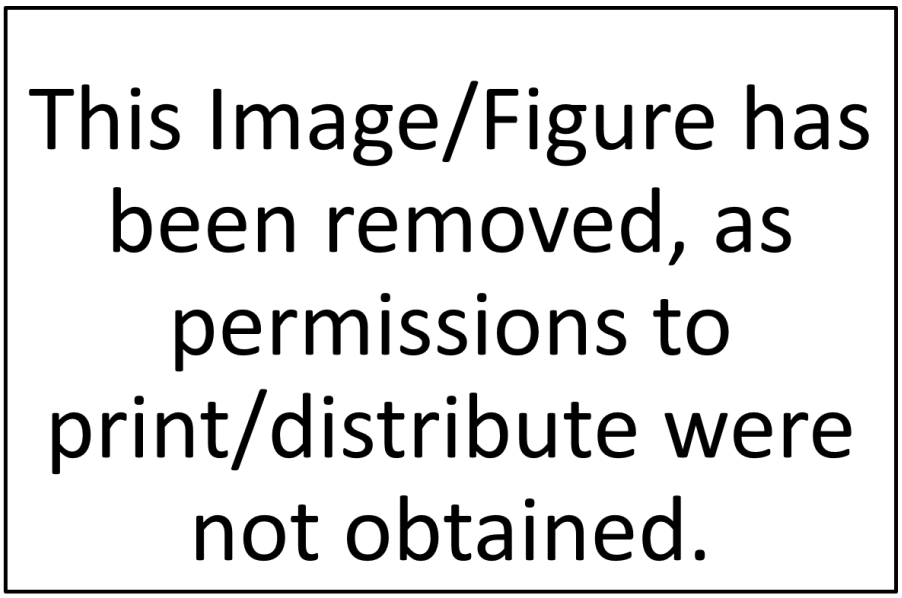

Figure 4.22: Plan of the archaeological features at Bradley Fen. Human remains are marked by red crosses (Appleby 2005: 24).

Two articulated skeletons were found within discrete graves. An adult male (Sk. 658) had been deposited within a grave that was subsequently truncated by a large prehistoric pit, leaving only the bones of the lower legs and feet *in situ* (Knight 2008, personal communication). Disarticulated bones presumably belonging to this individual had been deposited in the lower levels of the prehistoric pit. The position of the legs suggested that the body had originally lain in a crouched position on the left side orientated east-west or southeast-northwest. Concretions of iron panning adhered to some of the bones of this individual (Knight 2008, personal communication).

Image 4.2: Sk. 573 (right) and Sk. 853 (left) recovered from Bradley Fen. Sk. 853 had been deposited head-first in a watering hole and Sk. 573 had been squashed into a partly-backfilled post hole (courtesy of Mark Knight, CAU).

The articulated bones of an adult male (Sk. 785) were found in a second discrete shallow grave. The torso was prone and the lower legs had been flexed to the right. There was evidence of rodent damage on some of the bone surfaces (Knight 2008, personal communication). There was no mention of whether this damage was likely to have been caused by burrowing rodents that accessed the grave after the body had been deposited.

The body of an older middle adult female (Sk. 853) had been deposited head first in a watering hole (Appleby 2005: 19; Knight 2008, personal communication) (Image 4.2). The skeleton was recovered from the basal silt, which suggested that it represented a final deposit before the well was abandoned and left to silt up (Appleby 2005; Knight 2008, personal communication). The wrists of this skeleton were crossed and hands lay in front of the chest, which suggested that they may have been bound when the body was deposited (Appleby 2005: 19; Knight 2008, personal communication). The position of the body suggested that there had been no attempt to break the fall and that the individual was probably dead before they were deposited (Dodwell 2008, personal communication). The bones of this individual had been stained a dark brown/black colour and some had been covered in grey concretions. A piece of loose-woven textile was found adhered to this individual's left femur (Knight 2008, personal communication).

None of the skeletons from Bradley Fen had been radiocarbon dated. The stratigraphic relationships between the skeletons and dateable features suggested that the majority of the burials dated to the Late Bronze Age (Appleby 2005). For instance, Skeletons 853 and 573 were deposited in the later stages of features that could be associated with Late Bronze Age activity (Appleby 2005). The isolated shallowly-buried Sk. 785 was allocated a Late Bronze Age/Early Iron Age date, although the justification for this later date was not stated explicitly (Knight 2008, personal communication).

The waterhole that contained Sk. 853 skeleton was designed to allow access to the water table all year round and had probably been waterlogged from the point of deposition (Knight 2008, personal communication). The body would have remained inundated during decomposition (Appleby 2005). The loss of water from this context is likely to have occurred as a result of 17th century A.D. draining of the fens (Appleby 2005). The dark staining of the Sk. 853 skeleton was consistent with the bones having spent long periods of time within a waterlogged anoxic environment (O'Connor *et al.* 2011). This kind of staining is often attributed to the infiltration of the bone by humic factors that were mobile within the wet environment (O'Connor *et al.* 2011). The survival of the organic textile was also consistent with the grave having been rendered anoxic at or soon after deposition. This skeleton was recorded as originating from an anoxic environment.

Sk. 573 was surrounded by a fill of mid-brown sandy clay (Knight 2008, personal communication). The clay would not have been free-draining to the same extent as coarser soils, although it was unlikely that this environment would have been intrinsically anoxic (Janaway 1996; Dent *et al.* 2004; Carter *et al.* 2010). Sk. 573 had been buried towards the top of a post hole that was only 40 centimetres deep. This post hole formed part of a four-post structure which was situated on the northern terrace located around two metres above the ground water level (Appleby 2005; Knight 2008, personal communication). The sediments that surrounded these remains were not waterlogged at the time of the excavation and there was no persistence of organic grave goods (Knight 2008, personal communication). The bones did not demonstrate the dark staining that was apparent within Sk. 853. It was possible that the grave of Sk. 573 was waterlogged through the main period of its deposition, and only became aerated after the 17th century draining (Appleby 2005). Subsequent environmental interactions may have deleted signs of previous inundation. However, the same process had occurred within the context of Sk. 573, yet the taphonomic changes to this skeleton that had ensued as a result of waterlogging were still apparent (Appleby 2005: 19). The Sk. 573 was not recorded as having originated from an anoxic environment.

Sk. 785 and 901 were deposited within sandy clay sediments that were similar to those that surrounded Sk. 573. Both of these burials were located on the terrace associated with the Late Bronze Age settlement and the same uncertainties surrounded their taphonomic histories (Appleby 2005; Knight 2008, personal communication). It was unlikely that Sk. 785 had been waterlogged during decomposition as the grave of this skeleton was very shallow (Knight 2008, personal communication). The grave of Sk. 901 was deeper than that which contained Sk. 785, but was still relatively shallow. There was no evidence from the sediments or the preservation of organic material that these contexts had been previously waterlogged.

Skeletons from Bradley Fen were sampled for thin section analysis by the author for a Masters project that investigated whether there was any evidence for the practise of mummification in Later Prehistoric Britain beyond the discoveries made at Cladh Hallan (Booth 2008) (Table 4.13). The skeletons were held by the Cambridge Archaeological Unit. Permission to sample the remains had been provided by Mark Knight and Chris Evans, and the thin sections were still available within the collections at the University of Sheffield Department of Archaeology.

Thin sections were produced from fragments of bone taken from the left femoral anterior mid-shafts of Sk. 573 and 785 and the right femur of Sk. 853. Skeletons had been chosen for sampling based on their similarity to the Cladh Hallan remains, particularly in terms of evidence for deposition in unusual contexts and severe flexion of the body. The right femur of Sk. 853 was sampled to avoid having to disturb the preserved textile that adhered to the left element. All of the skeletons were articulated when they were discovered and so there was no repeat sampling of individuals. The thin sections of the Bradley Fen specimens did not require embedding and were prepared in the manner set out in the Methodology chapter. All of the skeletons sampled were articulated *in situ*, but the unusual nature of their deposition meant that they were viable for inclusion within the variably-treated Later Prehistoric cohort of remains. Sk. 853 and 573 had been deposited under novel circumstances in contorted positions, whilst the rodent gnawing observed on the bones of Sk. 785 indicated that this body might have been left to decompose in an open environment for a short length of time.

The Bradley Fen thin sections had originally been assessed using the OHI by the author during work for his Masters dissertation, but this assessment had not included detailed study of other diagenetic features (Booth 2008). The updated OHI scoring system developed by Millard (2001) had not been employed in the original assessment of the Bradley Fen thin sections. It was decided that the best approach was to reassess the Bradley Fen thin sections using the OHI whilst recording secondary diagenetic features.

Specimen	Age	Sex	Context
Sk. 573	Older Adult	Male	Manipulated into a backfilled post hole.
Sk. 785	Adult	Male	Shallow grave. Gnawed by rodents.
Sk. 853	Older Middle Adult	Female	Watering hole.

Table 4.13: Catalogue of the specimens that were sampled from the Bradley Fen site.

4.1.2.3 Bilham Farm, Brodsworth, South Yorkshire, U.K.

Figure 4.23: Map of the location of the Iron Age burial from Bilham Farm.

Brodsworth Hall is a Victorian country house located to the north-west of Doncaster in South Yorkshire. Brodsworth Hall's surrounding estate has been the subject of ongoing research and training excavations conducted by the Universities of Sheffield and Hull since 2006 (Figure 4.23). Numerous seasons of excavations have revealed features relating to phases of activity ranging from the Bronze Age enclosures to Victorian managed landscapes.

The 2009 series of excavations focussed on a prehistoric ditched enclosure that had been identified by geophysical survey near the location of the Bilham Farm water tower. The enclosure consisted of an egg-shaped arrangement of ditches that spread out into two track

ways leading off in opposite directions. Parts of the enclosure and the track ways were excavated in an attempt to retrieve dateable material. The stratigraphy of the site consisted of shallow topsoil over a limestone bedrock. This stratigraphy made it difficult to determine relationships between features (Merrony 2012, personal communication).

These excavations uncovered the articulated skeleton of an adult male that had been buried on a north-south orientation underneath one of the track ways (Merrony 2012, personal communication). The skeleton was accompanied by a canid tooth and a boar's tusk, both of which had been perforated. The legs of the skeleton were flexed, but the torso was prone, with the skull lying face down on the grave floor (McIntyre 2009). The torso, sacrum and right innominate had fallen away from the left innominate and the bones of the legs, which remained flexed on the left side. The body must have originally been placed in the grave flexed on its left side. The disarticulation of the skeleton suggested that the articulated torso and part of the pelvis were forced away from the left innominate and the legs after the soft tissues had partially decomposed (McIntyre 2009).

A second skeleton of a subadult individual was discovered in 2010 close to where the adult was found. The skeleton had been buried in a crouched position orientated north-south (Merrony 2012, personal communication).The skeleton had become badly fragmented by ploughing and was subsequently block lifted and excavated under laboratory conditions (Merrony 2012, personal communication).

Bone from the adult male skeleton yielded a radiocarbon date of 347-54 cal. B.C. (95% Confidence), placing the individual's death within the Iron Age. The two skeletons had been buried within two metres of one another. The subadult skeleton was assigned an Iron Age provenance by association (Merrony 2013, personal communication). The two skeletons had been stored at the University of Sheffield Department of Archaeology.

The burial sediment consisted of a heavy sandy clay. This sediment would not have been completely free-draining, but was not intrinsically anoxic. Only shallow levels of sediment covered the bedrock, and it was likely that the substrate had remained aerated over the period of burial (Merrony 2012, personal communication). There was no suggestion that the sediments or the interments had been subjected to frequent episodes of anoxia through waterlogging (Merrony 2012, personal communication).

Permission to sample the Bilham skeletons was granted by Colin Merrony. The bones of both of individuals were sampled for thin section analysis by the author using the procedures

outlined in the Methodology chapter. Samples of the anterior mid shaft of the left femur were taken in each case. The low number of samples was potentially problematic with regards to site specific interpretations of diagenesis. However, the Bilham bones were valid for inclusion as there was evidence that the adult skeleton had been manipulated *post mortem*.

4.1.2.4 Carsington Pasture Cave, Brassington, Derbyshire, U.K.

Figure 4.24: Map of the location of Carsington Pasture Cave.

Carsington Pasture Cave lies within the southern Peak District, around one kilometre east of Brassington village (Chamberlain 1999) (Figure 4.24). There are two entrances to the cave; a natural ground level passageway hidden within a north-facing hollow and an artificial vertical entrance six metres to the south, which was created by lead miners as an access shaft (Chamberlain 1999; Papakonstantinou 2009). The natural entrance opens into an initial chamber five metres in diameter, known as the entrance or flaccid chamber (Figure 4.26). The cave was explored and excavated by members of the Pegasus Caving Club and archaeologists from the University of Sheffield in 1998 (Chamberlain 1999). These explorations followed a

ten-metre-long passageway from the entrance chamber that terminated in a second chamber, known as the Yorick chamber. A vertical natural shaft led to a third chamber. Imprints of hobnail boots, pick marks and a clay pipe find suggested that there had been some previous mining activity within this chamber (Chamberlain 1999; Papakonstantinou 2009). No evidence for such activity was found within the other two chambers. The third chamber terminated in a four-metre-deep vertical shaft (Chamberlain 1999).

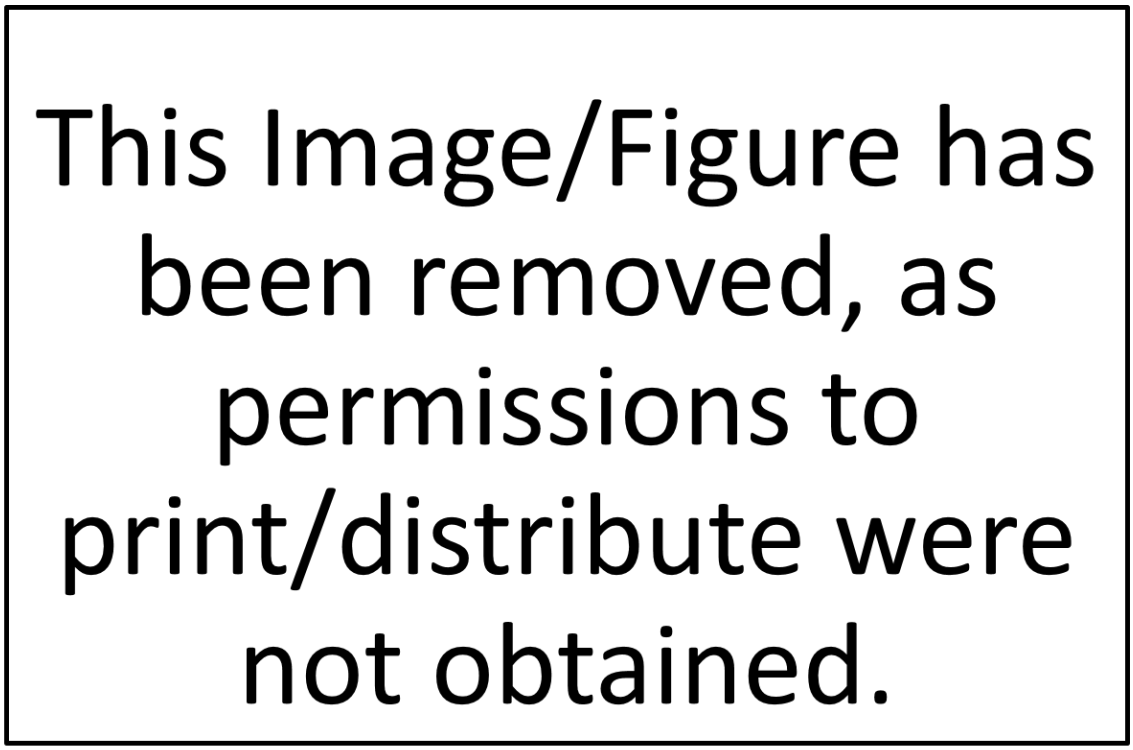

Figure 4.25: Projected vertical section of Carsington Pasture Cave (Chamberlain 1999: 4)

Quantities of disarticulated human and faunal remains were recovered from all chambers and adjoining passages (Chamberlain 1999) (Figure 4.26). There were no soil sediments within the cave. The bones were found lying directly on the chamber floors, which consisted of limestone and clay rubble (Chamberlain 1999). Some of the bones had been coated in speleothem (Chamberlain 1999: 4). All of the human and faunal remains were removed to the University of Sheffield (Chamberlain 1999). The human bones represented a minimum of twenty individuals (Papakonstantinou 2009). The frequency of human skeletal elements decreased with progression through the cave chambers (Chamberlain 1999: 4). The majority of the bones were recovered from the floor of the second chamber and the passage that connected this area to the third cavern. The distribution of the human bones throughout the cave suggested that the

second chamber was the primary focus of deposition (Chamberlain 1999: 4). Movement of bone from this chamber was probably encouraged by carnivore and rodent scavenging as well as movement of cave sediments (Chamberlain 1999; Papakonstantinou 2009). Marks indicative of carnivore gnawing were present on a small proportion of bones (Chamberlain 1999; Papakonstantinou 2009).

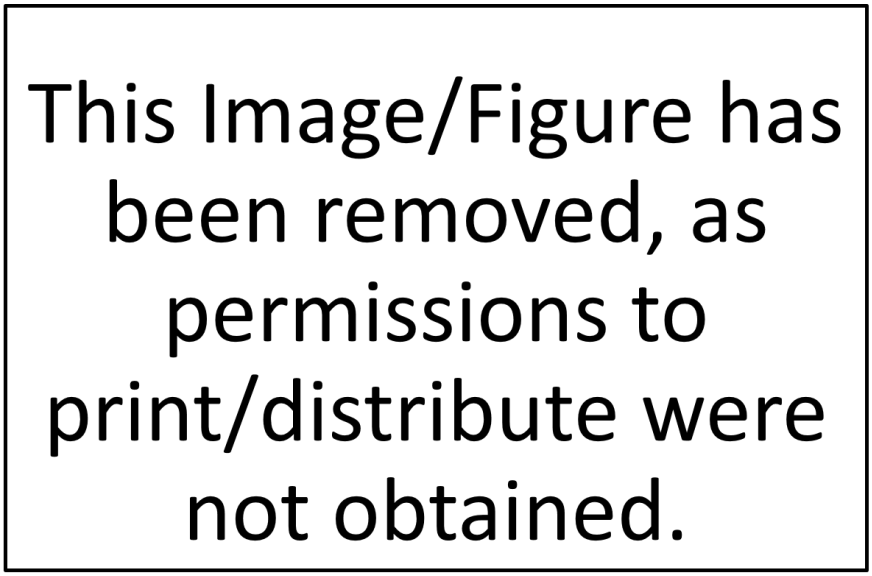

Figure 4.26: Plan of Carsington Pasture Cave with the position of the finds marked. Open circles represent the remains of neonatal individuals. The remains of children and adults are marked by closed circles (Chamberlain 1999: 4)

The human bone assemblage was dominated by neonates and mature adults (Chamberlain 1999: 6). The adult bones had been randomly dispersed amongst the cave chambers, but the neonatal deposits were concentrated at the centre of the second chamber. Papakonstantinou (2009: 30) attempted to allocate disparate bones to specific individuals based on visual pair matching, articulation, process of elimination and taphonomy (L'Abbé 2005; Byrde & Adams 2006). All of the bones from Carsington Pasture Cave had been disarticulated to some degree, although general anatomical relationships were still present in certain cases, which suggested that some of the bodies had been deposited in at least partial articulation (Chamberlain 1999; Papakonstantinou 2009). Lumbar vertebrae, sacra and pelvis bones of two individuals were found in close proximity within the passage located between the second and third chambers (Chamberlain 1999; Papakonstantinou 2009). The neonatal bones from the centre of the second chamber were all partially articulated (Papakonstantinou 2009: 30). A near-complete

partially articulated adult male skeleton was recovered from the second chamber (Chamberlain 1999: 6).

The human bone assemblage was characterised by a lack of small bones (Chamberlain 1999: 6). All of the bones from the cave demonstrated good macroscopic preservation and it was unlikely that skeletal part representation had been influenced by differential decomposition. However, a similar lack of small bones was also noted within the faunal assemblage from the site, which suggested that the dearth of small bones was a result of a systematic bias associated with the cave or excavation (Chamberlain 1999; Papakonstantinou 2009).

Cut marks were identified on three human femora (Chamberlain 1999: 7). Two of these femora were from opposing sides of the body and originated from a collection of material that lay in close anatomical proximity. Both of these bones may have come from the same individual. The cut marks were concentrated at articular ends rather than muscle attachment sites, which suggested that the purpose of the processing was to dismember rather than to deflesh (Chamberlain 1999; 7).

Less than 1% of the human bone assemblage demonstrated signs of weathering or carnivore alteration (Papakonstantinou 2009: 34). The cave was easily accessible and so the appearance of faunal damage could not be used to discriminate between immediate cave deposition and outdoor exposure (Papakonstantinou 2009; Mays 1998; Redfern 2008). No bones demonstrated root damage indicative of previous burial (Papakonstantinou 2009: 34). The lack of weathering suggested that it was unlikely that the bones had been exposed or buried elsewhere before being brought to the cave (Chamberlain 1999; Papakonstantinou 2009). The assemblage was probably formed through the deposition of whole bodies (Chamberlain 1999; Papakonstantinou 2009). These bodies were disarticulated through decomposition and subsequent disturbance by humans, fauna and natural karstic processes (Chamberlain 1999; Papakonstantinou 2009).

The dateable finds from the cave chambers suggested that there were multiple phases of activity. The species of fauna represented indicated that the cave was in use from around 4000 B.C. (Chamberlain 1999: 11). A bone pin from the second chamber was dated typologically to the Bronze Age. A worked antler fragment showed affinities with similar objects recovered from Neolithic sites (Chamberlain 1999). Subsequent excavations of other passages leading off from the entrance chamber located finds of Roman pottery and coins (Chamberlain 1999; Papakonstantinou 2009). The evidence for post-medieval mining activity suggested that the

cave was accessible from the Roman period up until modern times (Chamberlain 1999; Papakonstantinou 2009).

Three bones from the cave were radiocarbon dated (Chamberlain 2001). Two of these samples were human: one femur from the collection of neonatal bones recovered from the secondary chamber and one of the cut-marked femurs found in the passage connecting the second and third chambers. The third date came from an aurochs humerus that was collected from the passage between the second and third chambers. The aurochs humerus yielded a radiocarbon date of 4226-3770 Cal. B.C. (95% confidence), dating to the Early Neolithic (Chamberlain 2001). The cut-marked human femur provided a date of 2836-2292 Cal. B.C. (95% confidence), dating to the Late Neolithic/Early Bronze Age (Chamberlain 2001). The radiocarbon date of the neonatal bone was 760-402 Cal. B.C. (95% confidence), dating to the Late Bronze Age/Early Iron Age. These dates confirmed that use of the cave ranged from the beginning of the Neolithic and that there were at least two separate depositions of human remains, in the Late Neolithic or Early Bronze Age and the Late Bronze Age or Early Iron Age (Chamberlain 2001: 2).

It was unknown whether the human bone assemblage from Carsington Pasture Cave represented two episodes of deposition or the continuous interment of individuals over 2000 years (Chamberlain 1999; Chamberlain 2001; Papakonstantinou 2009). The position of the dated remains suggested that human bones recovered from the third chamber and the passage to the second chamber were probably Neolithic, whereas those remains recovered from the floors of the second chamber were more likely to be Iron Age. The close proximity of skeletal elements from the same individual in the second/third chamber passage inferred that these bones had remained within their original areas of deposition (Papakonstantinou 2009: 100). The exclusive concentration of cut marked bones within the same passage inferred that this collection of bones had been subjected to different funerary processes than those deposited within the second chamber (Chamberlain 1999; Papakonstantinou 2009). Further evidence for the limited mobility of remains between the second chamber and its passageway included the partial articulation of the male adult skeleton from the second chamber (Papakonstantinou 2009: 100). However, whilst plausible, this dichotomous chronological separation of bones between the Neolithic and Iron Age was reductive and uncertain. All of the human bones were recovered from the floor of the cave and had not been deposited in sediment. There was no suggestion that the cave had been subject to episodes of flooding that might have facilitated decomposition within an anoxic environment (Chamberlain 1999).

A neonatal tibia and femur from the Carsington Pasture Cave assemblage were sampled for thin section analysis by Economou (2003) and White (2009). These two samples had been embedded in LR White Resin and mounted onto slides using Euparal fluid. A further sixteen femora were sampled for thin section analysis for use in this project using the procedures outlined in the Methodology. The sampling was limited by the preference for the femur combined with the requirement to prevent duplicate sampling of individuals. All of the available left femoral fragments that included part of the mid-shaft and could not have constituted parts of the same bone were sampled. This strategy still allowed for a good representation of skeletal elements from throughout the chambers from remains that demonstrated evidence for diverse funerary treatment.

The Carsington Pasture Cave collection was available within the University of Sheffield Department of Archaeology. Economou (2003) had already assessed the two neonatal samples from Carsington Pasture Cave using the OHI. White (2009) had not used this scale in her reanalysis of the remains. The Economou samples had to be reanalysed for the assessment of birefringence, inclusions and infiltrations using the strategy outlined in the Methodology chapter. These samples were also reassessed using the OHI without any prior knowledge of their original scores. This scores recorded for the current study were consistent with those allocated by Economou (2003).

Specimen	Age	Sex	Chamber	Articulation
Y-072	Adult	Unknown	Second	Disarticulated
98-019	Adult	Unknown	Second	Disarticulated
98-040	Adult	Unknown	Second	Disarticulated
98-208	Adult	Female	Second	Disarticulated
98-314	Adult	Unknown	Second Passage	Dismembered – cut marks
98-315	Adult	Unknown	Second Passage	Disarticulated
98-316	Adult	Female	Second Passage	Disarticulated
98-317	Adult	Female	Second Passage	Disarticulated
FL-236	Adult	Unknown	Entrance	Disarticulated
FL-237	Adult	Female	Entrance	Disarticulated
FL-238	Adult	Unknown	Entrance	Disarticulated
FL-239	Adult	Unknown	Entrance	Disarticulated
Y?-047	Adult	Unknown	Second	Disarticulated
Y-03-066	Adult	Male	Second	Partially Articulated
Y-059	Adult	Unknown	Second	Disarticulated
CPC-Y-07	Adult	Female	Unknown	Disarticulated
CPC99-21	Neonate	Unknown	Second Chamber	Partially Articulated
CPCY03	Neonate	Unknown	Second Chamber	Partially Articulated

Table 4.14: Catalogue of the human remains samples from the Carsington Pasture Cave assemblage.

4.1.2.5 Cladh Hallan, South Uist, Outer Hebrides of Scotland, U.K.

Cladh Hallan is located to on the west coast of the island of South Uist, which makes up part of the Outer Hebrides archipelago in Scotland, U.K. (Figure 4.27). The site was excavated between 1999 and 2002 by staff and students from the Universities of Sheffield, Bournemouth and Winchester (Parker Pearson *et al.* 2004; 2005). The excavations revealed a series of multi-phased prehistoric features. The main focus of the excavations was a group interconnected stone roundhouses (Parker Pearson *et al.* 2004). Three of the northernmost houses were fully excavated (Parker Pearson *et al.* 2005: 530).

Figure 4.27: Map of the location of Cladh Hallan

The Cladh Hallan human remains were discussed to some extent in the Background chapter. This section will provide more detail and contextual information to what has already been explained. Human remains representing at least five individuals were excavated from underneath the peaty floors of the roundhouses (Parker Pearson *et al.* 2004; 2005) (Figure 4.28). The positions of the skeletons suggested that they represented foundation deposits linked to the initial construction of the roundhouses, rather than the remnants of an earlier

cemetery (Parker Pearson *et al.* 2005: 533). Three skeletons were excavated from the north house, one from the central house, and one from the southern house (Parker Pearson *et al.* 2004). An isolated unphased disarticulated human femur was recovered from a disturbed section of the site, which brought the number of individuals represented up to six (Summerfield 2004).

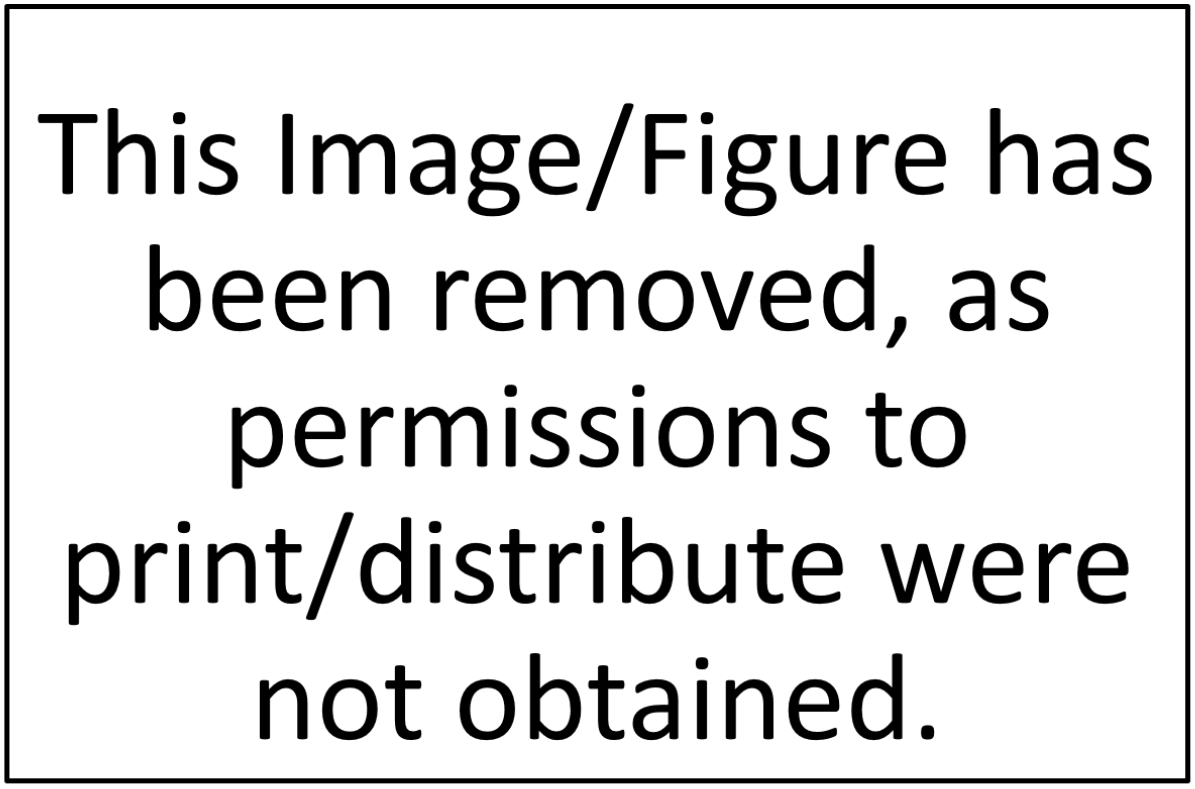

Figure 4.28: Plan of the Cladh Hallan roundhouses with the position of the remains (Parker Pearson et al. 2005).

The typology of the roundhouses suggested that they dated to the Late Bronze Age/Early Iron Age (Parker Pearson *et al.* 2004; 2005). The conjoined nature of the roundhouses indicated that they had all been built at around the same time (Parker Pearson *et al.* 2005: 532). Optically-stimulated luminescence (OSL) dates of the sand cores that underlay the shared walls suggested that this building took place between 1250-630 B.C. (Parker Pearson *et al.* 2005: 537) Radiocarbon dates of barley grains that lay on the floor of the north house dated to 1260-970 cal. B.C. (Parker Pearson *et al.* 2005: 537). All of the individuals represented by the skeletons must have been buried underneath the houses between 1260-840 cal. B.C. Markov Chain Monte Carlo sampling of the accumulated radiocarbon dates provided dates of roundhouse construction at 1330-1100 cal. B.C. (68% probability), the construction of the

floors (and sealing of the burials) at 1100-930 cal. B.C. (68% probability) (Parker Pearson *et al.* 2005: 537). These dates suggested that activity was concentrated at the end of the Bronze Age and at the beginning of the Iron Age.

The articulated skeletons of an adult male, an adult female and an infant were recovered from below the northern roundhouse (Parker Pearson *et al.* 2004; 2005). An articulated flexed skeleton of a juvenile and the partially disarticulated remains of a three-year-old child were recovered from under the central and southern roundhouses respectively (Parker Pearson *et al.* 2004; 2005). The bones of the three-year-old were found in their correct positions relative to one another, but only the vertebrae and the pelvis lay in anatomical articulation (Parker Pearson *et al.* 2004: 74). The partially-articulated nature of the skeleton suggested that the body had decomposed in a separate context before it was interred (Parker Pearson *et al.* 2004: 74).

The adult skeletons recovered from the northern roundhouse ostensibly appeared to represent two articulated burials. The adult female skeleton had been subjected to unusual *post mortem* treatment (Parker Pearson *et al.* 2004; 2005). The upper lateral incisors had been removed and placed in the hands (Parker Pearson *et al.* 2005: 534). The lack of damage to the tooth roots or the alveolar margin as well as the absence of healing suggested that the teeth had been removed *peri* or *post mortem*. The distal right femur, proximal tibia and patella (constituting the knee) of this skeleton had been broken away and placed in a separate pit (Parker Pearson *et al.* 2007). The character of the break was consistent with the event having occurred when the bone the bone had lost its moisture (Parker Pearson *et al.* 2007). The exact timing of the transformation from wet to dry bone is uncertain, but is thought to take around three months (Wheatley 2008; Wieberg & Wescott 2008). The broken fragments of the distal femur and proximal tibia lay in correct articulation within their separate context, suggesting that they still retained some soft tissue when they were deposited (Parker Pearson *et al.* 2007). The distal right radius of the same skeleton had been broken away and placed within a cremation pit. These observations suggested that the body had remained accessible for an extended period after death whilst retaining soft tissue (Parker Pearson *et al.* 2005; 2007).

Osteological analysis of the adult male individual discovered that the mandible was unlikely to have belonged with the skull that it accompanied (Parker Pearson *et al.* 2005: 534). The cervical vertebrae of this skeleton demonstrated changes consistent with osteoarthritis (Parker Pearson *et al.* 2005: 534). However, the rest of the vertebrae were free from degenerative changes. It was argued that this articulated individual had been constructed from the partially

articulated parts of three different people representing the post-crania, the cranium and neck and the lower jaw (Parker Pearson *et al.* 2005: 534).

The revelation that the male skeleton was constructed out of parts of several individuals led to suspicions regarding the adult female skeleton, particularly because there was already evidence that it had been treated unusually (Parker Pearson et al 2005). Ancient DNA analysis of the mandible, humerus and femur suggested that these bones had not originated from a single individual (Hanna *et al.* 2012). This skeleton was also an amalgamation of anatomical parts from at least three individuals (Hanna *et al.* 2012). There were no signs of disturbance within either of the grave cuts or the skeletons themselves, and so it was unlikely that these *post mortem* changes had occurred after burial through later exhumation of the remains (Parker Pearson *et al.* 2005; 2007).

Radiocarbon dating of the different parts of each adult skeleton as well as the bones of the three year old child revealed further anomalies. The cranium and mandible of the adult male skeleton yielded dates of 1500-1260 cal. B.C. and 1500-1210 cal. B.C. respectively (Parker Pearson *et al.* 2005: 537). The tibia of this skeleton was dated to 1620-1410 cal. B.C. The femur of the adult female skeleton produced a date of 1370-1050 cal. B.C. The femur of the three-year-old child dated to 1440-1130 cal. B.C. These dates were surprisingly early and remarkably dispersed considering that the roundhouses were built between 1330 and 1100 B.C., and the foundation burials must have taken place between 1100 and 930 B.C. (Parker Pearson *et al.* 2005: 537).

The radiocarbon dates from some of the bones did not overlap with the OSL dates for the overlying floors (Parker Pearson *et al.* 2005). This result suggested that certain parts of the adult and child skeletons were already old before they were interred (Parker Pearson *et al.* 2005). The radiocarbon dates from the child inferred that decades and even centuries had passed before it was inhumed (Parker Pearson *et al.* 2005: 537). This time period would normally have promoted complete skeletonisation, yet the partial articulation of this skeleton indicated that there was still soft tissue present when it was deposited (Rodriguez & Bass 1983; 1985; Janaway 1996; Campobasso *et al.* 2001; Breitmeier *et al.* 2005; Vass 2011; Fereira & Cunha 2013). The early radiocarbon dates of the two adult skeletons were also anomalous when it was considered that they were found in partial articulation (Parker Pearson *et al.* 2005: 537). The long duration between death and burial should have ensured the disarticulation of these remains had they decomposed normally (Rodriguez & Bass 1983; 1985; Janaway 1996; Campobasso *et al.* 2001; Breitmeier *et al.* 2005; Vass 2011; Fereira & Cunha 2013). The level of

articulation present within the post-crania of both adult skeletons suggested that the bones were still held in anatomical position by soft tissue when the bodies were interred (Parker Pearson *et al.* 2005: 537).

The articulation of the parts present within the Cladh Hallan skeletons does not make sense based on conventional knowledge of bodily decomposition (Micozzi 1986; Maureille & Sellier 1996; Micozzi 1991; Duday 2006). The sequence in which different parts of the body disarticulate is highly variable, but there is an accepted general order. For instance, bones of the neck, fingers, toes as well as the mandible are weakly articulated by small quantities of soft tissue and are usually amongst the first structures to collapse (Micozzi 1991; Duday 2006). The humerus of the adult female from Cladh Hallan represented a separate individual to the rest of the post-crania (Hanna *et al.* 2012). The humerus was articulated with a radius and ulna, carpals, metacarpals, and the majority of the phalanges of the fingers (Parker Pearson *et al.* 2004: 75). It would be unusual for the shoulder joint, which is surrounded by strong ligamentous tissue, to decompose before the labile finger joints (Micozzi 1991; Duday 2006). The patterns of articulation observed amongst the adult Cladh Hallan skeletons were similar to the paradoxical patterns of decomposition observed within formerly mummified disarticulated skeletonised remains (Maureille & Sellier 1996; Parker Pearson *et al.* 2005).

Parker Pearson *et al.* (2005; 2007) argued that mummification represented the best explanation for the *post mortem* manipulation and radiocarbon dates of the Cladh Hallan remains. This conclusions was supported by the histological analysis of bone from the adult male skeleton that has already been discussed (Parker Pearson *et al.* 2005). Preserved soft tissue must have been lost through subsequent interactions with the burial environment (Parker Pearson *et al.* 2004; 2005). Changes to the bone mineral within the tibia of the adult male measured by FTIR and SAXS were consistent with the body having been placed within a sphagnum bog, and this scenario was proposed as the possible method of mummification (Parker Pearson *et al.* 2005: 542). The burial sediment that surrounded all of the skeletons recovered from the Cladh Hallan consisted of a free-draining calcareous machair sand (Parker Pearson *et al.* 2004; 2005). The burial environment should have remained aerated during the process of decomposition and it was unlikely that any of the burials experienced episodes of anoxia due to waterlogging in this context (Parker Pearson *et al.* 2004; 2005).

A selection of the human Cladh Hallan skeletons were sampled for thin section analysis by Summerfield (2004) as part of a Master's dissertation that aimed to characterise the histological preservation of bone from the site as well as investigate whether there was any

further evidence that skeletons had been mummified previously. Summerfield's (2004) sampling strategy targeted long bones from a diverse range of skeletons. Thin sections were produced from femora and humerii. Thin sections had also been produced from the mandible and cranium of the adult male skeleton, which had been determined to represent parts of separate individuals (Summerfield 2004).

The majority of the remains from the site had already been sampled by Summerfield (2004), and it was felt that further sampling would be redundant (Table 4.15). Summerfield focussed on long bones, and so the thin sections fit the criteria of sampling for the current study. It would have been preferable to have examined the femora of the three-year-old and fourteen-year old remains, but extra sampling could not be justified given that samples of equivalent long bones from the same individual were available. The thin sections taken from the cranium and the mandible associated with the adult male skeleton were not included in the analysis. All of the thin sections bar those of the three-year-old could be prepared without having to be embedded. The humerus sample from the three-year-old was embedded in LR Acrylic White Resin. The sections were mounted onto microscope slides using Euparal.

Summerfield (2004) assessed the histological preservation of the Cladh Hallan thin sections using the OHI. Reanalysis of the Cladh Hallan thin sections was required to record extra diagenetic features. OHI was reassessed in each case without prior knowledge of Summerfield's scores. The histological preservation of the adult male had been published in the article by Parker Pearson *et al.* (2005), although this paper did not include the specific OHI score. The results from the rest of the remains had not been published, and were only to be found within Summerfield's (2004) Masters dissertation.

Specimen No.	Age	Sex	Element	State	Treatment
CH 2638	35-39	Male	Femur	Partially Articulated	Mummification
CH 2316	45+	Female	Femur	Partially Articulated	Mummification
CH 2792	3	-	Humerus	Partially Articulated	Mummification
CH 2727	10-14	-	Humerus	Articulated	Burial
CH C	Adult	-	Femur	Disarticulated	Unknown

Table 4.15: Catalogue of the human remains that were sampled from the Cladh Hallan assemblage.

4.1.2.6 Cnip Headland, Isle of Lewis, Outer Hebrides of Scotland, U.K.

Figure 4.29: Map of the location of the Cnip Headland site.

Cnip is a small township in the Parish of Uig on the west coast of the Isle of Lewis, in the Outer Hebrides of Scotland (Figure 4.29). The Cnip headland lies to the east of the township and projects into the sea inlet of Loch Roag. Human remains were observed within a stone feature located in the base of a deflation hollow by members of a local historical society in 2008 (Lelong 2011). A team of archaeologists from the Glasgow University Archaeological Research Division (GUARD) excavated and assessed the cist and the surrounding area on behalf of Historic Scotland (Lelong 2011). The work uncovered human remains in various stages of articulation. Skeletal part representation suggested that at least twelve discrete individuals were represented (Knott 2011; Lelong 2011). The remains were taken back to the University of Glasgow and assessed by the GUARD osteoarchaeologists Olivia Lelong and Carol Knott (Knott 2010; Lelong 2011).

Excavation of the cist and the surrounding area revealed three separate collections of human skeletal material, termed Area A, Area C and Area D. Area A encompassed a three-sided capped stone cist (Lelong 2011). The walls of the cist had been consolidated with piles of sand. A small hollow had been dug into the bottom of this sandy layer to accommodate the remains

of a male individual (Sk. 1) (Lelong 2011: 8) (Figure 4.30). The dental development of this individual suggested an age-at-death of fourteen years (Lelong 2011, personal communication). This result contrasted slightly with the state of femoral epiphyseal fusion, which indicated that the individual must have been over sixteen (Lelong 2011, personal communication). The excavators speculated whether this skeleton represented the partially articulated remains of two individuals (Lelong 22011, personal communication). However, that disparity between the dentition and the post-crania was slight, and could be explained by natural variation (Lelong 2011, personal communication).

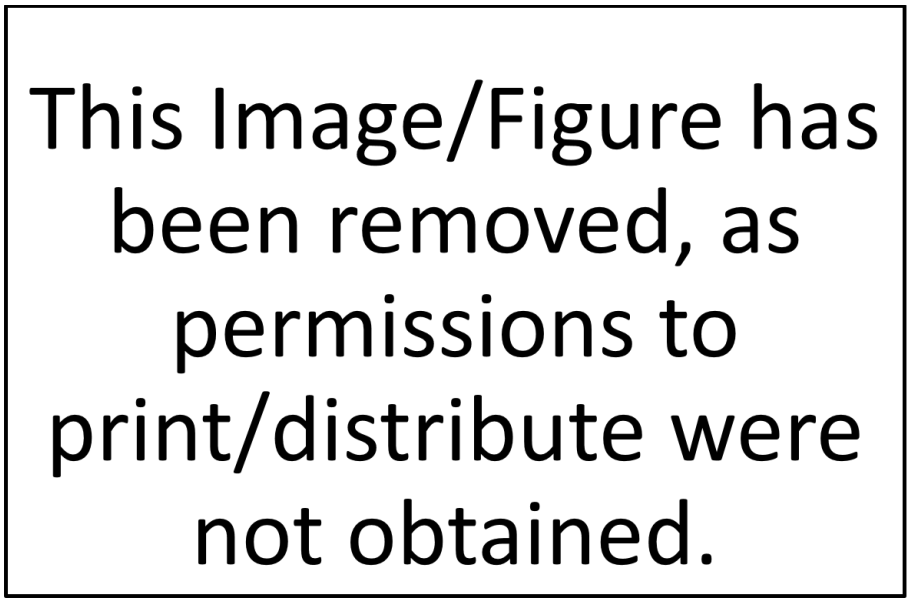

Figure 4.30: Plan of Sk. 1 from Cnip within its cist (Lelong 2011: 8).

Sk. 1 was originally thought to represent an articulated inhumation that had been buried supine in a tightly flexed posture (Lelong 2011: 13). However, closer examination revealed that many of the bones of this individual were missing or disarticulated (Lelong 2011: 13). The cranium and the first cervical vertebrae were separated from the torso by burial sediment, which indicated that they had not been in articulation when they were deposited (Lelong 2011: 13). Several of the thoracic vertebrae were out of alignment with the rest of the vertebral column. The bones of the thorax were also separated from the pelvis by undisturbed burial sediment. The left leg was only represented by a fibula, which was found by the cranium. Several of the lumbar vertebrae were missing. There was no associated disturbance of the burial sediments that may have indicated that disarticulation had occurred as a result of later activity (Lelong 2011: 13). Sk. 1 was covered in wind-blown sand which had probably entered the cist after though gaps in the stonework. The soils that surrounded the skeleton

had been stained a red-brown colour. This staining intensified with proximity to the bones and probably represented dispersions of decomposition products (Lelong 2011, personal communication).

A fourth left metacarpal and a fifth left metatarsal were recovered from the packing sand below the lower leg of Sk. 1 (Lelong 2011: 13). These bones lay half a metre beneath the approximate position of the right foot of the main burial (Lelong 2011, personal communication). The size, state of epiphyseal fusion and colour of these bones indicated that they did not belong to the right foot of the Sk. 1 and must have represented a second individual (Lelong 2011, personal communication). Several other small human bones and teeth were recovered from the wind blow sand deposited around the burial and beneath the capping stones. Replication of skeletal elements and relative sizes of these bones suggested that they had not originated from the main interment (Lelong 2011, personal communication). The excavators suggested that the bones were from an earlier burial that was removed to accommodate the semi-articulated inhumation (Lelong 2011: 13). The main burial was accompanied by finds of a perforated boar's tooth and a tooth of a juvenile seal.

Area C was located two metres to the south of the Area A cist (Figure 4.31). This section of the site consisted of a sand mound consolidated by a partial stone kerb. Disarticulated human bones representing two adults, an infant and a subadult of indeterminate age had been placed on top of the mound (Lelong 2011, personal communication). This assemblage predominantly consisted of bones from the thorax, hands, feet and cranium (Lelong 2011: 14). These bones were associated with a copper alloy awl and had been covered by a layer of sand.

A second deposition of disarticulated human bones representing two adult females, an infant and a child of six or seven had been placed in top of this sand layer (Lelong 2011: 14). This deposit consisted of similar types of disarticulated bones to those that were found in the first layer, but also included a pelvis and long bones. Some of the bones lay in partial articulation, which suggested that soft tissue decomposition had not completed before they had been deposited (Lelong 2011: 15). Two small amalgamations of bones appeared to represent the deposition of an articulated hand and foot (Lelong 2011: 15). However closer inspection revealed that these groups were composed of combinations of hand and foot bones, which were interpreted as representing a deliberate effort to reconstruct anatomical parts (Lelong 2011: 15). Closer examination of an articulated pelvis revealed that only one of the innominate bones belonged with the sacrum and that the other originated from a separate individual (Lelong 2011: 15). The bones from the second layer of Area C were also surrounded by dark

soil the colour of which intensified with proximity to the bone (Lelong 2011: 15). Two jet beads were found in association with this layer of human remains.

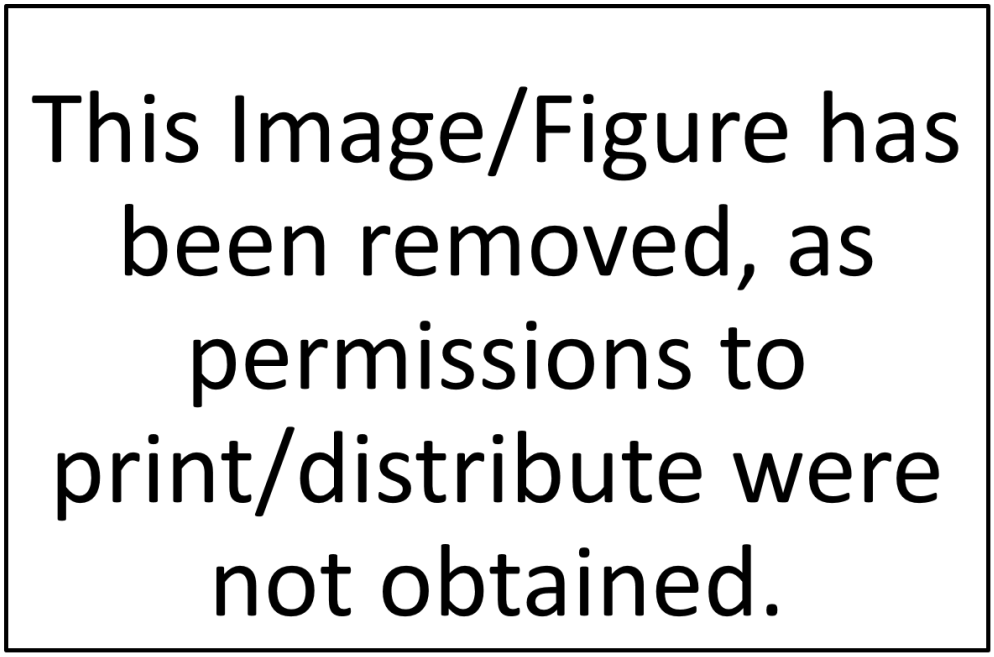

Figure 4.31: Schematic plan of the disarticulated human remains recovered from Area C at Cnip (Lelong 2011: 16).

Area D was uncovered two metres to the north of the Area A cist. A shallow grave had been dug into the sand to accommodate the flexed body of an articulated neonatal infant (Sk. 3) (Knott 2010). The sand that surrounded this burial was discoloured brown, which may have occurred as a result of the decay of organic material or by the dissipation of bodily decomposition products (Knott 2010: 8). The body of the infant was accompanied by various marine shells. Another shallow hollow had been dug above this grave to accommodate the body of a 40-44 year old female (Sk. 2) (Knott 2010: 7) (Figure 4.32). The skeleton was in a poor condition, but the positions of the legs suggested that it had been deposited in a tightly flexed posture (Knott 2010). The presence of small proximal hand phalanges suggested that this burial had disturbed the infant inhumation that lay underneath. The disarticulation of the hand phalanges indicated the infant had skeletonised before it was disturbed (Knott 2010). There were suggestions that the adult individual was only partially articulated when it was deposited (Knott 2010). The left femur articulated correctly with the rest of the bones of the leg but the femoral head was 0.18m away from the acetabulum of the pelvis (Knott 2010: 8). There was no evidence of disturbance to the burial sediments that surrounded the body. The adult

individual may have been interred in a partially articulated state after having decomposed elsewhere.

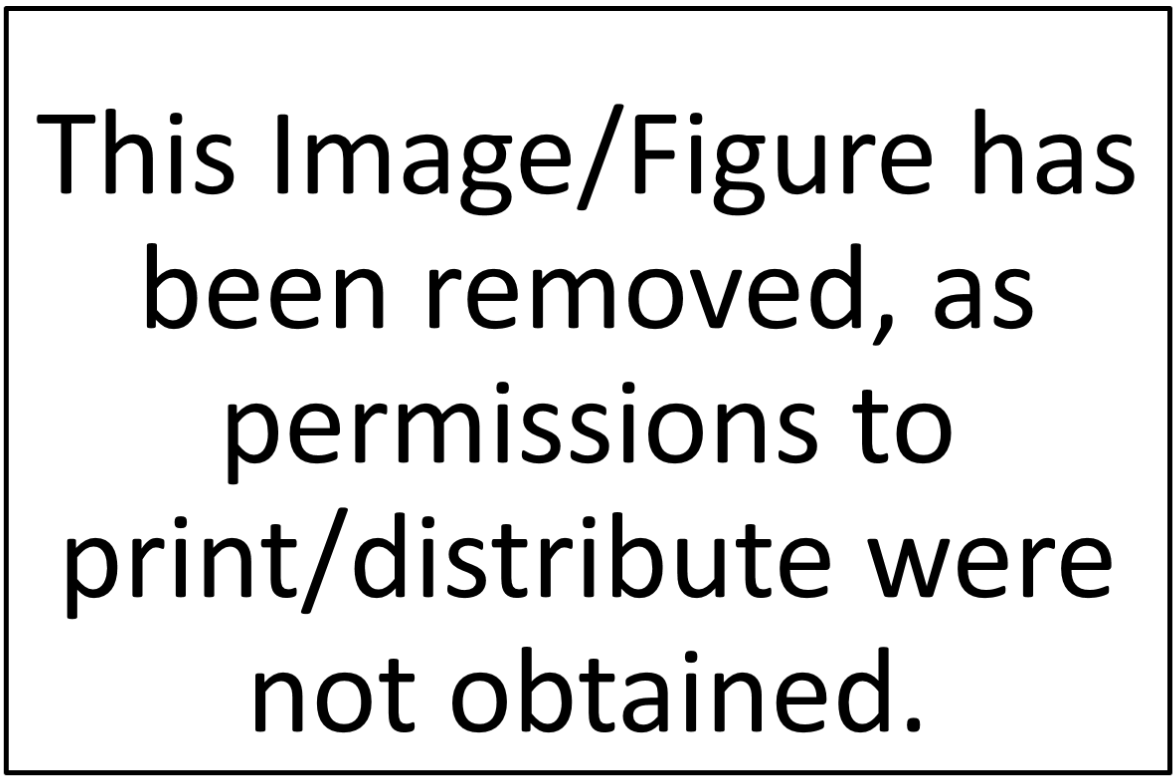

Figure 4.32: Plan of the adult female skeleton from Cnip Area D (Knott 2010: 8)

The human remains recovered from all areas of the Cnip site were subject to an extensive program of radiocarbon dating encompassing fifteen bones from across all of the lettered areas (Lelong 2011, personal communication). Remains from all contexts dated to the same period; 1900-1530 cal. B.C., placing the death of the individuals within the Early to Middle Bronze Age (Lelong 2011, personal communication). Bayesian modelling radiocarbon dates suggested that burial activity began in 1795-1695 cal. B.C. (95% probability) and ended 1745-1650 cal. B.C. (95% probability) (Lelong 2011, personal communication). This model assumed that burial took place soon after death. The typologies of the jet beads and the bronze awl found amongst the disarticulated remains in Area C were consistent with an Early Bronze Age date (Lelong 2011: 14).

The burial sediments at Cnip varied in colour, but were consistently composed of calcareous machair sands (Knott 2011: Lelong 2011). Sandy soils such as these are coarse, free-draining, and not naturally anoxic (Janaway 1996). It was unlikely that the sands would have promoted

episodic periods of anoxia by waterlogging. There was no significant preservation of organic grave goods. There was no evidence to suggest that the burial contexts had ever been anaerobic.

All of the Cnip Headland bones were held at the University of Glasgow. Permission to sample the remains was granted by Dr. Olivia Lelong. The sampling strategy was to obtain specimens that were representative of the different funerary treatments and the diverse areas of excavation. The left femur was missing from the partially-articulated Sk. 1 from Area A and the right femur had to be sampled instead. The partial articulation of this skeleton meant that it was likely that all of the bones originated from the same individual.

The disarticulation of the second individual represented within Area A suggested that it had been treated differently to the primary skeleton. It was pertinent to obtain representations of two potentially different funerary rites from the same context to test whether diagenesis could vary within bones from separate individuals obtained from the same grave. Unfortunately the only bones that were available to sample from the second Area A individual were not conventional long bones. The mid-shaft of the 5th left metatarsal found beneath Sk. 1 was sampled. This bone was deemed appropriate for inclusion within the current study as it is classed as a long bone and the ratio of cortical and trabecular structures is similar that observed within bones such as the femur (White *et al.* 2012). It had to be conceded that the sampling of this bone was problematic, as its anatomical position within an extremity located away from the abdomen might have protected it from the deleterious actions of putrefactive visceral bacteria (Jans *et al.* 2004). The results from this specimen would be monitored carefully and compared within other remains from the site before they were included within the overall analysis.

Only two femora were recovered from Area C, a left and a right. The fragment of the right femur was only a partial mid-shaft, but was much smaller than the comparative part of the left femur, which indicated that these two bones were unlikely to have been antimeres (Lelong 2011, personal communication). Both femora were sampled. The right femur from Area C could not have come from the main burial from Area A as the whole of the right femur of Sk 1 was present. The femur of Sk 1 demonstrated a fused proximal epiphysis, whereas the same epiphysis on the left femur from Area C was unfused (Lelong 2011, personal communication).

It was decided that an additional sample should be taken from another partially articulated bone to capture more variation in funerary treatment. No femora lay in partial articulation within Area C, and so a different long bone had to be selected. The only relevant long bones

available were an articulated radius and ulna (Lelong 2011: 15). The radius was sampled. The inclusion of a new skeletal element from the same area of deposition raised the risk of sampling from the same individual multiple times. However, epiphyseal fusion and size of the radius and ulna indicated that these elements originated from an adult (Lelong 2011, personal communication). Size and state of epihphyseal fusion of both femora from Area C indicated that they had originated form subadult individuals (Lelong 2011, personal communication). The complete fusion of the distal epiphysis of the ulna also ruled out the possibility that the two bones originated from Sk. 1, as the distal epiphysis of the Sk. 1 ulna was unfused (Lelong 2011, personal communication). Both the neonatal and adult burials retrieved from Area D retained fragments of their left femora and both of these elements were sampled (Knott 2010; Lelong 2011, personal communication). All of the remains were sampled for thin section analysis for using the techniques outlined in the Methodology chapter (Table 4.16). All samples could be cut without embedding.

Area	Specimen	Element	Age	Sex	Articulation
A	Sk 1	R. Femur	14-20	Unknown	Partially Articulated
A	SF 54B	5th L. Metatarsal	Adult	Unknown	Disarticulated
C	SF 20	R. Femur	Subadult	Unknown	Disarticulated
C	SF 50	L. Femur	Subadult	Unknown	Disarticulated
C	SF 19	R. Radius	Adult	Unknown	Partially Articulated
D	Sk 2	L. Femur	40-44	Female	Partially Articulated
D	Sk 3	L. Femur	Neonatal	Unknown	Articulated

Table 4.16: Catalogue of the human remains that were sampled from the Cnip Headland assemblage.

4.1.2.7 Danebury Hillfort, Hampshire, U.K.

The substantial earthworks known as the Danebury Hillfort have been investigated by archaeologists since the 19th century (Figure 4.33). The main excavations of the site were undertaken by archaeologists from the Universities of Southampton and Oxford between 1969 and 1978 (Cunliffe 1983; 1984). This work was initiated as a research excavation funded by Hampshire County Council, the Department for the Environment, a number of academic bodies and commercial companies, as well as the Universities of Southampton and Oxford (Cunliffe 1983; 1984).

Figure 4.33: Map of the location of the Danebury hillfort.

The Danebury hillfort began as an area of around five hectares enclosed by a timber-framed rampart and a ditch (Cunliffe 1983: 49) (Figure 4.34). Two entrances were situated on opposite sides of the enclosure and connected by a roadway. The central part of the site and the area spreading north of the main road were filled with rows of four-post structure that were interpreted as granaries (Cunliffe 1983: 103). The area of the hillfort that lay to the south of the road was occupied by postholes of circular houses (Cunliffe 1983: 96). The areas in between the houses were filled with groups of granaries and pits.

The southern area of the hillfort was used for the construction of large four and six post granaries (Cunliffe 1983: 106). These structures were laid out along the internal roads. A number of quarries were established within the hillfort, concentrated towards the outside of the enclosure, on the lee of the ramparts. Storage pits were located in specific clusters all around the site (Cunliffe 1983; 1984). Towards the end of the Iron Age, the southwest entrance was blocked off. The gates were burnt down, leaving the enclosure entirely undefended. This event that was taken to signal the abandonment of the hillfort (Cunliffe

1983: 172). Occupation of the site continued after this burning event, but on a much smaller scale (Cunliffe 1983: 181).

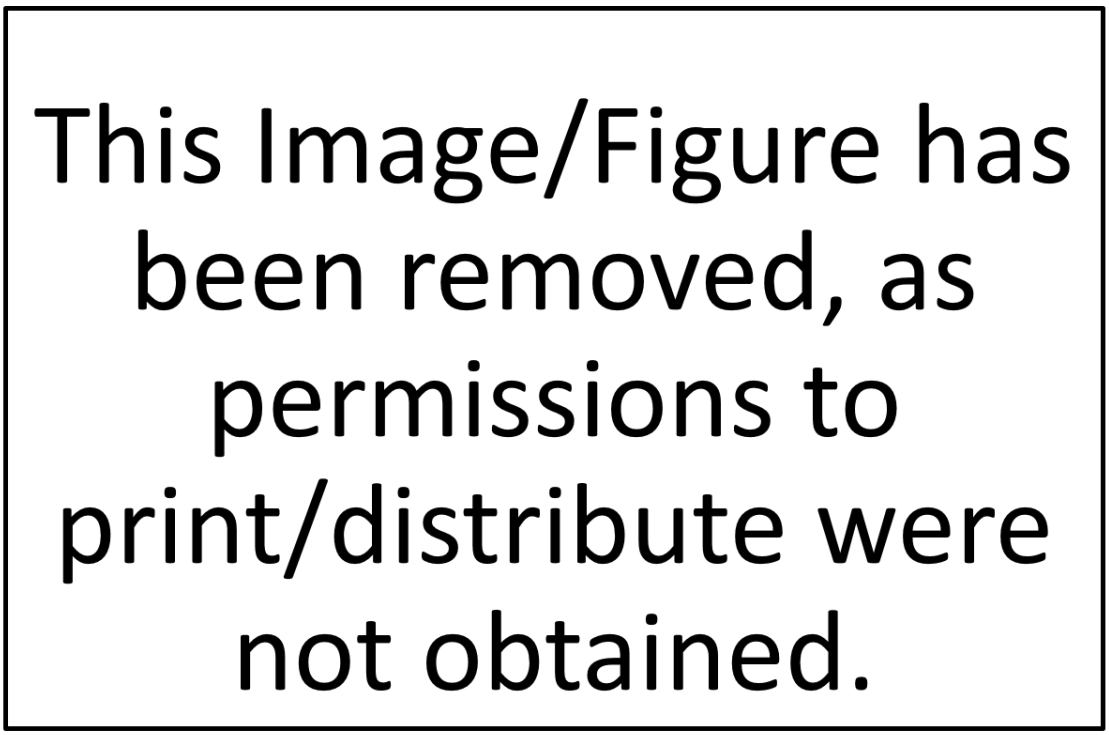

Figure 4.34: Plan of the excavated parts of the Danebury hillfort during the later phases of occupation (Cunliffe 1983: 71).

Cunliffe (1983: 66) developed seven ceramic phases through the study of the pottery recovered from Danebury. The stratigraphic position of the pottery types helped to establish a sequence of ceramic phases that was used to link the different aspects of the site. These ceramic phases were dated and corroborated by sixty radiocarbon dates of associated bones, charcoal and other organic remains (Cunliffe 1983: 65; Buck *et al.* 1992). Recalibration and Bayesian modelling of the dates by Buck *et al.* (1992) reemphasised the sequence of the pottery phases but also demonstrated that there was substantial overlap. However, all of the radiocarbon dates confirmed that the site was occupied from the Early to the Late Pre-Roman Iron Age (Cunliffe 1983; Buck *et al.* 1992) (Table 4.17).

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Ceramic Phase	Cunliffe Original Dates (cal. B.C.)	Buck *et al.* (1992) Upper Date Range (cal. B.C.)	Buck *et al.* (1992) Lower Date Range (cal. B.C.)
1-3	550-450	830-430	380-120
4-5	450-400	860-410	330-140
6	400-300	650-410	260-A.D. 20
7-8	300-100	450-240	70-A.D. 100

Table 4.17: Table of the original dates allocated to the Danebury ceramic phases along with Buck et al.'s (1992) estimations based on the Bayesian analysis of radiocarbon dates.

The southern area of the hillfort was used for the construction of large four and six post granaries (Cunliffe 1983: 106). These structures were laid out along the internal roads. A number of quarries were established within the hillfort, concentrated towards the outside of the enclosure, on the lee of the ramparts. Storage pits were located in specific clusters all around the site (Cunliffe 1983; 1984). Towards the end of the Iron Age, the southwest entrance was blocked off. The gates were burnt down, leaving the enclosure entirely undefended. This event that was taken to signal the abandonment of the hillfort (Cunliffe 1983: 172). Occupation of the site continued after this burning event, but on a much smaller scale (Cunliffe 1983: 181).

The ways in which human remains had been deposited at Danebury varied considerably (Cunliffe 1983; 1984). The different types of depositions were separated into six categories; whole bodies, individual incomplete skeletons, multiple partially articulated skeletons in charnel pits, skulls, pelvis girdles and other individual bones/bone fragments (Cunliffe 1983: 162). The number of individuals represented in each burial context varied significantly. All categories of remains were recovered as part of burials of single and multiple individuals (Cunliffe 1984). Most skeletons had been deposited on top of domestic refuse or silt (Cunliffe 1983: 1984). Certain remains had been covered by a layer of natural silt, which suggested that some of the pits had been left open whilst the remains decomposed (Cunliffe 1984: 448). Cut marks were identified on one set of remains (Cunliffe 1983: 163). Only a small number of the bones demonstrated evidence for carnivore or rodent gnawing (Cunliffe 1984: 463).

Twenty-five individuals were represented by depositions categorised as whole bodies (Cunliffe 1984: 443). All but one of the articulated skeletons were found in postures that demonstrated variable degrees of flexion. The extent of flexion could be used to divide the articulated assemblage (Cunliffe 1984: 443). The tight and unstable positions of bones within the hyper-flexed skeletons suggested that these bodies had been wrapped or trussed (Cunliffe 1984: 443).

The remains that were included within the 'individual incomplete skeletons' category consisted of single interments that were missing specific anatomical elements (Cunliffe 1984: 451). These deposits included articulated skeletons that were missing the skull and bones of the arms (Cunliffe 1984: 451). This pattern of anatomical loss was consistent with scavenging by carnivores (Micozzi 1986; 1991). The frequency of skull deposition across the site and its common absence from partially-disarticulated remains suggested that the skull or the head retaining some significance after death (Cunliffe 1983: 164).

Two contexts were labelled as charnel pits, as they contained mixed assemblages of partially-articulated remains (Cunliffe 1984: 451) (Image 4.3). Sling stones were recovered from both of the contexts, which suggested that their inhabitants may have been the victims of ritual slaughter (Cunliffe 1984; 451). Both of the charnel pits belonged to the late period of occupation. Isolated skulls were recovered from variably-dated contexts, although the majority originated from the latest phases (Cunliffe 1984). A disarticulated skull of a child was found with the mandible in articulation, which suggested that the head had been removed before decomposition had completed (Cunliffe 1984: 452: Micozzi 1991). The mandibles associated with the rest of the skull deposits were absent, which suggested that these skulls had been redeposited as dry bones after decomposition (Cunliffe 1984: 452). Single fragmentary pelvic girdles were recovered from four pits (Cunliffe 1984: 453). The girdles were associated with early and late phases.

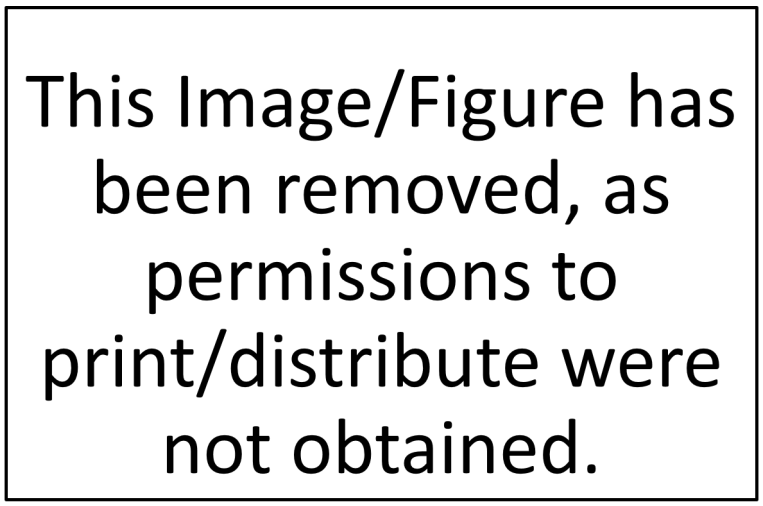

Image 4.3: Charnel pit P1078 from Danebury, which mostly included deposits of partially articulated bodies (Cunliffe 1984: 445).

The disarticulated human bone assemblage represented a minimum of thirteen people from 116 contexts in 77 pit, two post holes, one gully and quarry hollows behind the ramparts (Cunliffe 1984: 454). Disarticulated bones were recovered from more contexts than the rest of the human remains combined (Cunliffe 1984: 457). Small bones, such as those of the hands and feet, or vertebrae were often recovered in association with other bones of the same or adjoining anatomical parts (Cunliffe 1984: 457). There was good representation of bones from all parts of the body, although there was a noticeable lack of bones from the torso (Cunliffe 1984). Smaller elements, such as teeth and vertebrae were more often recovered from contexts assigned to the later phases (Cunliffe 1984: 454). A proportion of the isolated long bones had been fragmented. The fresh nature of the breaks suggested that the bones had been broken soon after death (Walker 1984: 455). Larger proportions of disarticulated bones demonstrated signs of carnivore gnawing compared to articulated or partially articulated skeletons (Cunliffe 1984: 454).

All of the skeletons from Danebury had been surrounded by a mixture of domestic refuse, chalk rubble and silts (Cunliffe 1983; 1984). Chalk is a porous stone, and it was unlikely that the sediments or the chalk bedrock would have retained water in a way that would have caused frequent saturation and anoxia. There was no extraordinary persistence of organic tissue or materials that might have indicated previous anoxic environments. It was assumed that the majority of individuals interred at the Danebury site had decomposed under aerobic conditions.

The bones from Danebury were kept at the Hampshire Museum Service. Permission to sample the remains was granted by Dave Allen. Eighteen of the Danebury human bones were sampled for thin section analysis. The strategy of the sampling was to capture variation in funerary treatment and phase to encompass the maximum levels of potential variability in mortuary treatment. The skull and pelvic girdle deposits were excluded. The sample set was focussed on all deposits that included femora. The isolated partial skeletons and partially disarticulated charnel deposits were combined, as they both represented accumulations of partially articulated remains. Six random specimens from each of these categories were selected for sampling by ranking the remains using a random number generator in Microsoft Excel. The articulated inhumation sample list was divided into two based upon the degree of flexion of the skeleton, as the potential presence of wrappings represented further variation in treatment. Three samples were taken from flexed and hyper-flexed articulated assemblages respectively. Samples of bones were obtained from contexts that demonstrated a spread of ceramic phase affiliations, but the bias in representation meant that the majority of samples originated from the later stages of occupation.

Some of the bones that were chosen could not be located on the day of sampling and replacement specimens had to be taken. The impact of this setback was limited and the distribution of bones samples amongst temporal phases and stages of disarticulation remained the same. The need to focus sampling on femora meant that five specimens of disarticulated skeletal elements were obtained instead of six and the missing sample was replaced by a sample of a partially-articulated femur. In certain cases the left femur was absent, or the right femur had been sampled previously. A right femur was only sampled from articulated individuals or those partially articulated remains where the antimere was present. One sample was taken from an isolated disarticulated right femur. No other bones were recovered from this context. The bone was checked against sampled left femora that had not been accompanied by a matching right element to test whether it was a likely antimere.

One of the partially-articulated specimens did not include any femora. The state of skeletal articulation within this individual was unique and it was decided that a sample from this individual should still be included. The left tibia was sampled in lieu of the missing femora. All of the Danebury samples were taken specifically for use in the current project and were prepared using the procedures outlined in the Methodology chapter (Table 4.18). The remains did not require embedding in order to be thin sectioned.

Pit	Deposit No.	Age	Sex	Ceramic Phase	Deposit Type	Element
26	BG 14	Unknown	Unknown	7	Individual Bones	Femur
923	40	25-30	Female	6	Multiple partially articulated	Femur
10	72	Adult	Unknown	6	Individual Bones	Femur
1015	46	20-25	Male	7	Whole bodies	Femur
1078	162	Adult	Male	7	Multiple partially articulated	Femur
120	7	~8	Indeterminable	8	Incomplete Skeletons	Femur
1993	214	25-30	Female	7	Incomplete Skeletons	Femur
2044	275	Adult	Unknown	6	Individual Bones	Femur
2100	248	>35	Female	3	Whole bodies	Femur
2447	239	18-22	Male	7	Incomplete Skeletons	Femur
2605	259	>50	Female	7	Whole bodies	Femur
266	10	20-30	Female	3	Incomplete Skeletons	Tibia
374	13	3	Unknown	3	Whole bodies	Femur
699	127	Adult?	Unknown	6/8	Individual Bones	Femur
761	130	Adult?	Unknown	8	Individual Bones	Femur
829	28	25-35	Male	6	Whole bodies	Femur
829	29	25-35	Male	6	Whole bodies	Femur
923	37	16-20	Female	6	Multiple partially articulated	Femur

Table 4.18: Catalogue of the human remains sampled from the Danebury Hillfort assemblage.

4.1.2.8 Frälsegården, Falbygden, Vastra Götalands, Sweden

Frälsegården is a small farm that lies within the Falbygden region of the Västra Götalands County in south-western Sweden (Sjögren 2010) (Figure 4.35). From 1999 to 2001, a team of archaeologists from the University of Gothenburg excavated a megalithic passage tomb located on the land associated with the Frälsegården farm (Sjögren 2012, personal communication). The passage tomb consisted of a southeast-facing sealed entranceway that led into a long chamber positioned on a northeast-southwest axis (Sjögren 2010). The typology of the Frälsegården passage tomb placed it within a narrow date range between 3300 and 3000 B.C. (Sjögren 2010). Eight-thousand-three-hundred-and-eighty-one human bone fragments were recovered from within the passage tomb, which represented at least 51

individuals (Sjögren in prep.). The articulation of the bones was highly variable, ranging from entirely disarticulated discrete elements to fully articulated skeletons (Sjögren 2010) (Figure 4.36).

Figure 4.35: Map of the location of the Frälsegården site.

Some of the partially-articulated skeletons were described as bone 'packages', consisting of mostly-complete skeletons that had been manipulated into tightly flexed arrangements (Sjögren 2010; Sjögren 2012, personal communication). The disarticulated anatomical elements were distributed evenly throughout the chamber and part of the entranceway (Sjögren 2012, personal communication). The articulated and mostly-complete skeletons were concentrated within the centre of the chamber, near the entrance and against the western wall. No disarticulated remains were recovered from underneath the near-complete skeletons, which suggested that the centre of the chamber had been kept clean up until the interment of the articulated remains, or that the area was cleared in order to accommodate the new depositions (Sjögren 2012, personal communication). Two separate funerary rites were suggested to have been practised at the site, one which led to the disarticulation of the remains and one that variably preserved bodily form (Sjögren 2010; Sjögren 2012, personal communication). The high level of flexion observed amongst the articulated remains and the bone packages suggested that these bodies had been wrapped (Sjögren 2010).

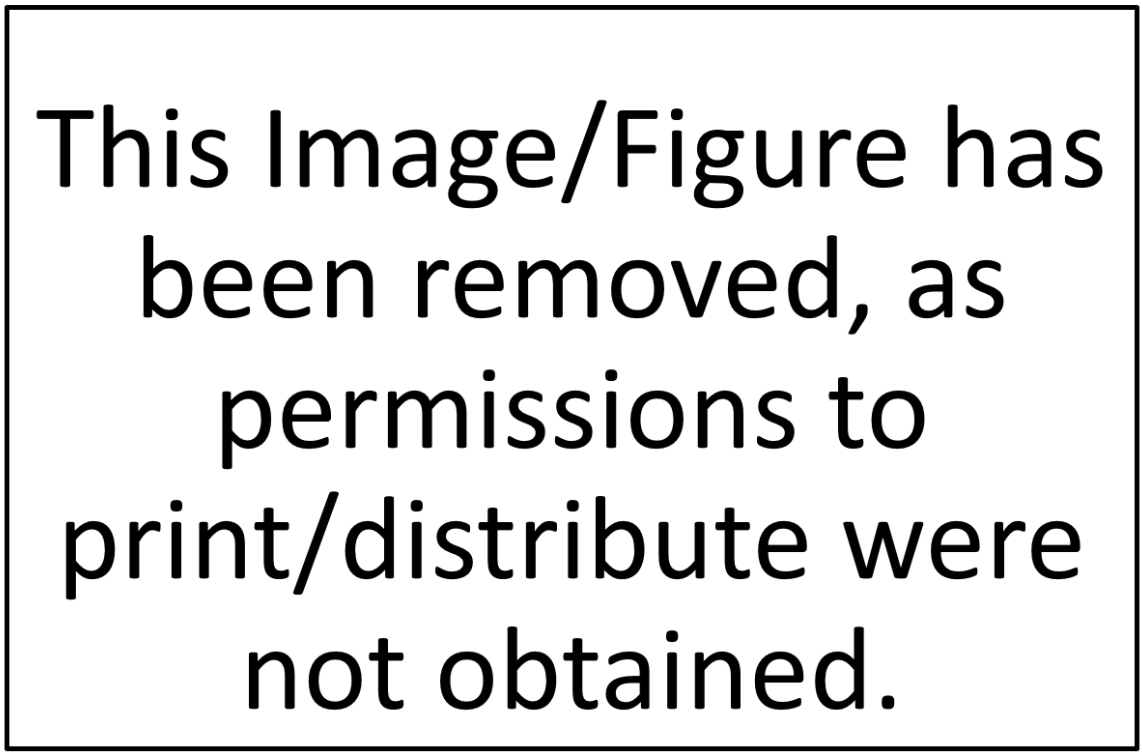

Figure 4.36: Plan of some of the skeletons recovered from the Frälsegården tomb. The remains demonstrate varying positions and levels of anatomical articulation (Sjögren 2010: 14).

All of the bones retrieved from the Frälsegården passage tomb were examined for the presence of cut marks and scavenger gnawing in an attempt to determine methods of disarticulation (Sjögren 2012, personal communication). No markings that could be attributed to tool processing were found on any of the bones. Two bones demonstrated evidence for rodent gnawing (Sjögren 2012, personal communication). None of the bones from Frälsegården demonstrated patterns of weathering consistent with surface exposure. These results indicated that it was unlikely that the remains had been excarnated by sub-aerial exposure (Sjögren in prep).

The Frälsegården human were subjected to an extensive program of radiocarbon dating, which placed all of the remains within the Swedish Middle Neolithic; 3100-2900 cal. B.C. (Sjögren 2012, personal communication). Bayesian modelling of the radiocarbon dating from the articulated and partially articulated skeletons produced a narrower range of deposition between 3000-2900 cal. B.C. (Sjögren 2012, personal communication). The distribution of the radiocarbon dates for the articulated and disarticulated remains were significantly different

and suggested that the interment of disarticulated remains had ceased 100-200 years before the deposition of the articulated skeletons (Sjögren 2012, personal communication).

The Frälsegården remains were originally thought to lie outside of the geographical scope of the current study. However, the inclusion of these samples would improve the potential variation in funerary treatment represented by the Later Prehistoric samples. The inclusion of another site also bolstered the Later Prehistoric sample size. There is evidence from Britain and Sweden for deposition of disarticulated and partially disarticulated remains within different forms of barrows and chambered tombs during the Neolithic (Darvill 2010; Sjögren 2010). Climatic conditions are considered to predominantly affect how a body decomposes and may have had some effect on putrefactive bone bioerosion (Rodriguez & Bass 1983; 1985; Campobasso *et al.* 2001; Fernández-Jalvo *et al.* 2010; Vass 2011). However, the Frälsegården site lies within temperate Europe on a similar latitude to northern Scotland, and so seasonal patterns of decomposition would have been within the British range.

The evidence from Frälsegården suggested that the majority of individuals decomposed within the empty chamber of the passage tomb (Sjögren 2010). However, the monument and the interments were subsequently covered by sediment over the thousands of years after the tomb fell out of use. The burial sediment was composed of glacial till, a heterogeneous mixture of clay, sands and gravels (Sjögren 2012, personal communication). This type of soil would have been free-draining and not intrinsically anoxic. The free-draining nature of the soils would have prevented frequent episodes of anoxia by waterlogging. The position of the tomb on the ancient ground level suggested that it was unlikely that it was regularly flooded. There was no evidence for high levels of organic preservation at the site. There was no reason to believe that the natural decomposition of the remains within the Frälsegården tomb was altered by any factor other than anthropogenic treatment.

The bones from Frälsegården were held at the University of Gothenburg. Dr. Karl-Goran Sjögren granted permission to access the remains and arranged for samples to be sent to the University of Sheffield. The bones selected for sampling were grouped into skeletons that were articulated, partially articulated and disarticulated. Bones that could be attributed to separate individuals were selected by Karl-Goran Sjögren. It was hoped that this strategy would help to capture the full variation of funerary rites practised at the site, particularly with regards to the differential treatment afforded the temporally-distinct disarticulated and articulated remains.

Ten of the individuals from the Frälsegården assemblage were sampled for thin section analysis (Table 4.19). Three bones originated from articulated complete remains, three from

partially articulated skeletons and four consisted of disarticulated skeletal elements. All of the bones were sampled specifically for use in the current project and were produced and assessed using the techniques expounded in the Methodology chapter.

The samples were all taken from femora. Right femora were sampled from articulated remains where this element was significantly more fragmentary than the left. Right femora were sometimes sampled from partially articulated remains where the left femur was absent. Only a limited number of femoral fragments were recovered from the disarticulated assemblage. Disarticulated right femora were only sampled where they could be associated with a discrete individual. The researchers at the University of Gothenburg had performed rigorous comparative analysis of the replicate skeletal parts to provide a more accurate estimation of how many individuals were represented (Sjögren 2012, personal communication). All of the disarticulated or partially articulated femora that were sampled for thin section analysis could be confidently ascribed to separate individuals by bone size and state of epiphyseal fusion (Sjögren 2012, personal communication).

Specimen	Individual	Age	Sex	Articulation
123293	-	Adult	Unknown	Disarticulated
139267	B	30-40	Female	Articulated
130443	G	50-60	Female	Partially Articulated
138105	A	20-30	Female	Articulated
119236	-	Adult	Unknown	Disarticulated
132234	K	50-59	Male	Partially articulated
136163	AC	Adult	Unknown	Partially Articulated
134704	E	35-39	Female	Articulated
117150/115371	-	Adult	Unknown	Disarticulated
124039	-	Adult	Unknown	Disarticulated

Table 4.19: Catalogue of the human remains sampled from the Frälsegården assemblage.

4.1.2.9 Hornish Point, South Uist, Outer Hebrides of Scotland, U.K.

Hornish Point is a headland located at the northwest tip of the island of South Uist, in the Outer Hebrides of Scotland (Figure 4.37). The Hornish Point site was excavated in 1984 by John Barber and Heather James with a team from the Scottish Development Department (Barber 2003). The sand cliff was excavated using a tapestry system whereby each stratigraphic context was assigned a block number and excavated in turn (Barber 2003). All of the blocks had been formed by the same depositional processes and lay in contact with one another in

sequence. Block 18 contained partial remains of the radial piers of a wheelhouse and associated deposits. Four pits averaging 0.4 metres in diameter and 0.8 metres in depth had been cut into Block 27, which lay directly underneath this wheelhouse (Barber *et al.* 1989; Barber 2003).

Figure 4.37: Map of the location of Hornish Point.

Human and animal remains were recovered from across the four pits (Barber *et al.* 1989). The bones had been deposited as a jumbled mass on top of a primary infill of brown sand (Barber *et al.* 1989: 774). Human bones originating from a single individual were recovered from across all four pits (Barber *et al.* 1989; Barber 2003) (Figure 4.38). Pit 1 contained a human lower right limb and part of the pelvic girdle, which were accompanied by the disarticulated skeleton of a complete juvenile bovid 18-30 months old (Barber *et al.* 1989). Human upper limbs, upper thorax and skull were recovered from Pit 2. Pit 3 held the bones of the lower thorax and the other half of the pelvic girdle as well as a clavicle, two ribs, a metacarpal, and the distal condyles of a femur. The bones from Pit 3 were mixed with substantial parts of the skeletons of two sheep, one over three years old and another 18-30 months. Only fragments of the human left foot were recovered from Pit 4, which contained most of the bones of a juvenile bovid (Barber *et al.* 1989). The human individual had died at around twelve years of age

(Barber et. 1989: 774). The sacrum of this skeleton demonstrated changes consistent with *spina bifida occulta*, a disorder where the sacral vertebrae do not close, leaving the spinal cord exposed (Barber *et al.* 1989: 774). This disorder would not have affected the individual in life and was unlikely to have had a significant visible manifestation on the body (Barber *et al.* 1989: 774). It was unlikely that this pathology would have affected bodily decomposition.

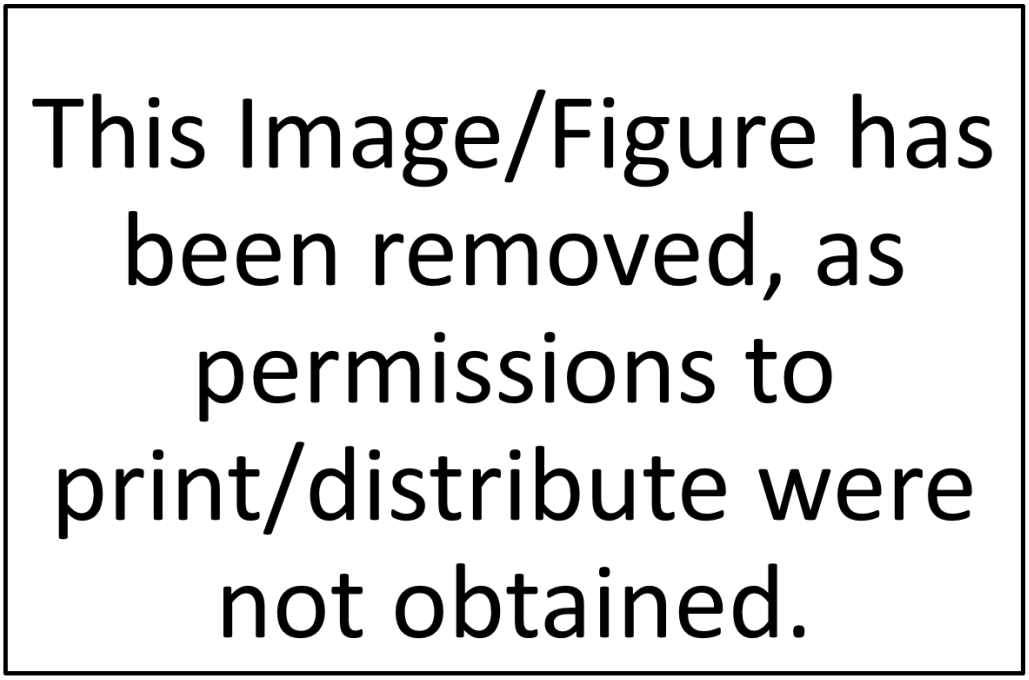

Figure 4.38: Plan of the position of the pits that contained the partially articulated remains of a juvenile individual within the radial walls of an Iron Age wheelhouse at Hornish Point (Barber et al. 1989: 774).

The human bones were recovered from their respective pits in a disarticulated state, but there were suggestions that the body was not fully skeletonised when it was deposited. The skeletal elements found in each pit originated from the same parts of the body, which suggested that anatomical relationships had been retained to some extent (Barber *et al.* 1989: 774). Some of the long bone epiphyses had not fused, yet most lay in articulation with their respective diaphyses, which indicated that they were still held together by soft tissue at the point of deposition (Barber *et al.* 1989: 775).

The fourth and fifth lumbar vertebrae of the Hornish Point individual demonstrated chop marks which indicated that the spinal column had been purposefully severed (Barber *et al.* 1989: 776). There was no way of determining whether this treatment occurred around the time of death or in the early *post mortem* period, as a wound of this kind would have killed the

individual instantly (Barber *et al.* 1989: 777). The way in which the parts of the skeleton had been distributed throughout the pits broadly corresponded with the position of severance. Mutilation of the spine may have been carried out in order to distribute the remains amongst the four pits (Barber *et al.* 1989; Barber 2003). Barber *et al.* (1989: 777) suggested that the partial articulation of the body may be explained had the individual been lost at sea, only to wash up at a later point in a partially-decomposed state. The mutilation of the body and its distribution amongst the pits alongside structured deposits of domesticate bone may have represented ritual that was intended to counteract the ill effects of an inauspicious death (Barber *et al.* 1989: 778).

The bones from Hornish Point have not been dated directly. The architecture of the overlying wheelhouse is consistent with other structures found within this part of Britain that have been dated securely to the Iron Age (Barber *et al.* 1989; Barber 2003). Radiocarbon dates of sea-shells from Block 26, the sediment into which the four pits were cut and Block 4, which lay above the deposit containing the wheelhouse, produced bracketing dates of 2410+/-50 (735-395 cal. B.C.) and 2335+/-50 (732-210 cal. B.C.) respectively (Barber 2003). The Hornish Point human remains must have been deposited within the Early to Middle Iron Age (Barber *et al.* 1989: Barber 2003).

The burial sediments were composed of calcareous machair sand (Barber 2003). The coarseness of the sand would have ensured that the burial context remained free-draining and aerobic. The free-draining nature of the sands would have also prevented frequent periods of anoxia from waterlogging. There was no substantial organic preservation at the site. There was no reason to suggest that environmental factors may have interrupted the decomposition of the remains from Hornish point, although it should be noted that the exact environment in which this body decomposed initially was not known.

The bones of the Hornish Point individual were held at the National Museum of Scotland. Permission to sample the remains was granted by Dr. Alison Sheridan. The right femur of the Hornish Point juvenile was sampled for thin section analysis and analysed specifically for this study using the techniques outlined in the Methodology chapter. The right femoral mid-shaft was sampled rather than the left as this was the only side that was available on the day of sampling. The thin section was cut from this sample without prior embedding.

4.1.2.10 Langwell Farm, Strath Oykel, Sutherland, Scotland.

Figure 4.39: Map of the location of Langwell Farm.

Langwell Farm is located near the south banks of the River Oykel, southeast of the town of Lairg in Sutherland, in the Highlands of Scotland (Figure 4.39). In 2009, the landowner uncovered a large stone slab in a field near the banks of the River Oykel. Further investigation revealed that the slab covered a cist which contained an articulated human skeleton (Lelong 2009) (Image 4.4). The skeleton was covered in white powdery substance and a woven material (Lelong 2009). A team of archaeologists from GUARD excavated the remainder of the cist (Lelong 2009). The cist contained a flexed articulated burial of an adult female (Lelong 2012).

Image 4.4: Photograph of the skeleton in situ within the Langwell cist. The bones are covered by a white powdery substance and organic material, but no substantial sediment (Lelong 2009: 12).

The skeleton was visible from the opening of the cist and was only half buried (Lelong 2009: 12). Most of the soil that covered the skeleton had fallen in during the discovery of the grave. Pieces of preserved organic woven material were recovered from next to the head and the feet (Lelong 2009: 12). Organic material resembling hair was found covering the legs. Microscopic analysis identified this material as a cattle hide (Lelong 2012).

The white powdery sediment that was observed covering the body was initially thought to be adipocere (Lelong 2009: 14). Dark greasy sediment was found within the matrix surrounding the bones. This material appeared to be organic and was interpreted as products of bodily decomposition (Lelong 2009: 14). Amorphous organic material was found throughout the sediments in the cist, particular in those that surrounded the skeleton (Lelong 2009: 14) (Figure 4.40). More detailed chemical investigations found that the organic content of the white substance was low (Lelong 2012). Scanning electron microscopy and Energy-dispersive x-ray microscopy revealed that this substance consisted of gypsum crystals (Lelong 2012: 13). Gypsum is a soft form of calcium sulphate dihydrate that forms as a result of bone mineral decomposition (Lelong 2012: 13).

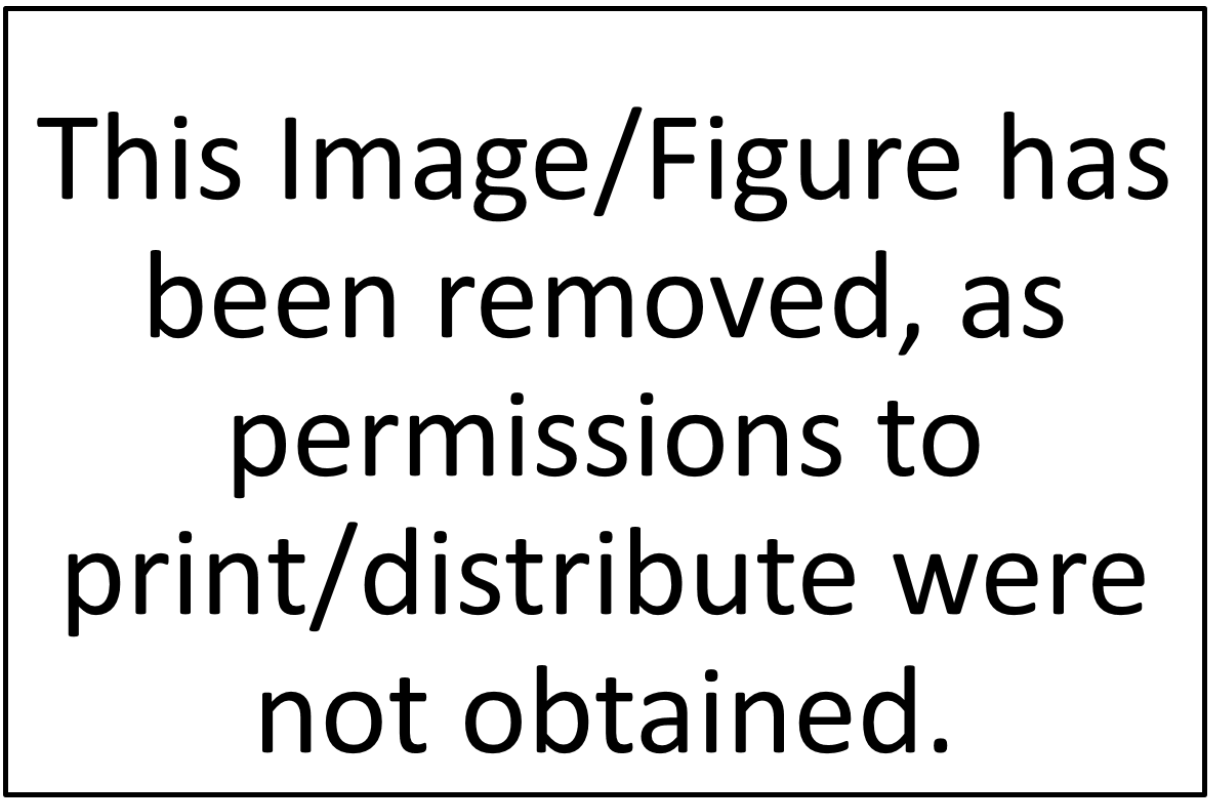

Figure 4.40: Plan of the inhumation from Langwell cist with associated deposits and organic materials (Lelong 2009: 15).

It was likely that the body had decomposed within the empty cavity of the cist rather than within the soil (Lelong 2009: 14). The soils in the cist consisted of red, yellow and grey sand (Lelong 2009). Sandy environments are usually free-draining and not intrinsically anoxic or prone to anoxia through retention of water (Janaway 1996). White mineral deposits that were found adhering to the inside of the cist consisted of calcium carbonate products of bone decomposition that had been deposited during periods of flooding (Lelong 2012: 13).

The soils sediments within the cist were a grey colour (Lelong 2009: 14). This colouring was most likely caused by periodic episodes of anoxia via waterlogging (Lelong 2012). Waterlogging had probably been promoted by heavy rainfall that raised the level of the adjacent River Oykel. The frequent inundation of the cist was likely to be responsible for the high levels of organic preservation (Lelong 2012). The Langwell skeleton was recorded as having been recovered from an anoxic environment.

The right ulna and the right fibula of the skeleton from Langwell Cist were radiocarbon dated along with a piece of the ox hide covering (Lelong 2012). Both the ulna and the ox hide

produced dates of 2130-1880 cal. B.C. (95% confidence) (Lelong 2012: 14). The fibula sample produced a radiocarbon date that was appreciably earlier than the other two, 2200-1960 cal. B.C. (95% confidence) (Lelong 2012: 14). All of the radiocarbon dates placed the death of the individual within the Early Bronze Age. The discrepancy between the dates from the different bones of the skeleton prompted the excavators to speculate whether it had been constructed from pieces of several individuals (Lelong 2011, personal communication). The possibility that the Langwell body had previously been curated was also suggested by the radiocarbon date of the cattle hide and basketry found in the cist, which were identical to the later date obtained from the human bone (Langwell 2012: 14). Radiocarbon dates mark the point of death, and so it might be expected that the dates from the basketry and cow hide would have been earlier than those from the skeleton. However it was possible that the organisms used to produce these items had died shortly before their interment within the cist (Langwell 2012: 14). Remains of parasites recovered from the cow hide supported this scenario (Langwell 2012: 14).

The bones of the Langwell individual were held at the University of Glasgow. Permission to sample the remains was granted by Dr. Olivia Lelong. The anterior left femoral mid-shaft of the Langwell individual was sampled and analysed using the techniques outlined in the Methodology chapter. The Langwell sections were cut without having to be embedded.

4.1.2.11 Neat's Court, Queensborough, Isle of Thanet, Kent, U.K.

The Neat's Court business park is located on the outskirts of the town of Queensborough, on the west side of the Isle of Thanet (Figure 4.41). In 2009 a strip, map and sample excavation of ground surrounding the Neat's Court site was undertaken by Swales & Thames Archaeological Survey Company in anticipation of a new development. This survey identified a buried mound in a section of the site named Area C. Archaeologists from MOLES Archaeology led by Geoff Morley were subcontracted to excavate Area C. Their excavations revealed the construction sequences of a prehistoric barrow.

The first mound was constructed out of alternate layers of turf and clay over a freshly-laid clay layer and had been surrounded by a clay bank. The mound measured around two metres in diameter and 0.5 metres high, but was subsequently enlarged with reworked clay and domestic refuse. A second mound was constructed over this enlarged structure. This second mound was also created from clay mixed with midden material (Morley n.d.). The bank of the mound was also enlarged at a later stage. The barrow was covered by alluvial deposits laid

down during two phases of alluvial/estuarine inundation (Morley n.d.). The first of these inundations surrounded the mound and the second covered it completely (Morley n.d.). The stratigraphic relationship between the alluvial deposits and the third raising of the bank suggested that the secondary building events had occurred in response to the inundation (Morley n.d.). These building phases may have represented an attempt to make the structure more visible above the inundation levels (Morley n.d.).

Figure 4.41: Map of the location of the Neat's Court round barrow.

Fourteen separate deposits of human bone had been inserted within the barrow complex. Seven of these individuals were represented by cremated inhumations, six by articulated inhumations and a seventh by a disarticulated interment (Figure 4.42). Four of the unburnt articulated burials were recovered from within the area of the primary mound. The homogeneous nature of the clays meant that grave cuts could not be located and the stratigraphic relationships between the burials and the construction sequences were undiscernible (Morley n.d.). It was not clear which burials were associated with each phase of the mound, although all burials originated from the clay and midden material rather than the pure clay layers. The levels taken from the four skeletons recovered from the mound indicated that they had all been buried at depths within ten centimetres of one another (Morley 2012

personal communication). The insertion of separate burials close together without any intercutting suggested that the bodies were buried within living memory of one another or were distinguished by perishable grave markers (Morley n.d.).

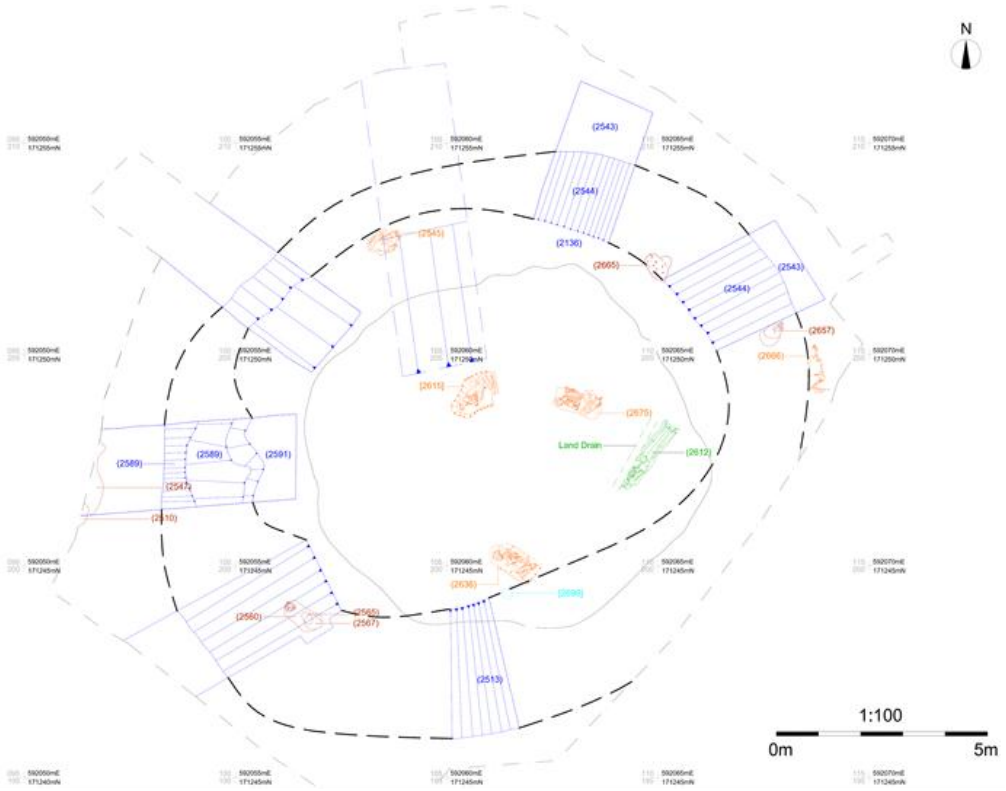

Figure 4.42: Plan of the Neat's Court barrow and associated burials (courtesy of Geoff Morley of MOLES Archaeology).

Three of the four articulated burials from the mound were recovered in flexed postures on their right sides. The fourth was found in an extended supine position (Image 4.5). The left arm and part of the left thorax of this skeleton had been lost through disturbance by a medieval drainage pipe. The atlas and axis vertebrae were missing, and the skull was found in an unusual position away from the remaining cervical vertebrae, which could be seen running underneath the mandible that was articulated with the displaced cranium. The temporo-mandibular joint is surrounded by minimal soft tissue and subsequently the mandible is one of the first bones that disarticulates *post mortem* (Micozzi 1991; Duday 2006). The articulation of the mandible and cranium of this skeleton suggested that the displacement of the skull had occurred soon after death.

Two articulated burials were excavated from outside of the mound structure. Both of these skeletons were recovered in flexed positions on their right sides and were recovered from the area between the mound and the surrounding bank. A seventh individual represented by

fragments of a skull and humerus was recovered from the surface of the mound. It was likely that these bones had been moved from their original context by ploughing (Morley n.d.).

Image 4.5: Sk. 2611 from Neat's Court in situ. The skull and superior vertebrae have been displaced but without any subsequent disarticulation of the mandible (Courtesy of Geoff Morley of MOLES Archaeology).

None of the artefacts recovered from the Neat's Court round barrow have been dated using absolute techniques. The nature of the burial sediment and the lack of grave goods meant that it was impossible to produce precise dates for burial. The episodes of alluvial inundation responsible for the burial of the Neat's Court Barrow correspond with rises in sea level that occurred towards the end of the Bronze Age and beginning of the Iron Age (Morley n.d.). This timing was supported by the typology of pottery recovered from within the inundation sediments (Morley n.d.). Articulated single inhumation within a round barrow is broadly associated with the Early Bronze Age and earlier phases of the Middle Bronze Age in Britain (Darvill 2010). The typology of the funerary rites afforded the individuals from Neat's Court would support an Early-Middle Bronze age date (Morley n.d.). Ceramic fragments located within the deposits underneath the mound could be dated typologically to the Beaker period of the Early Bronze Age (c.2400-2000 B.C.) (Morley n.d.). These artefacts provided an upper bracket for the date of the barrow (Morley n.d.).

The most securely dated feature was a furnished cremation that had been inserted within the barrow mound. The cremated bone was found spilling out of a Collared Urn that could be

dated typologically to the Early-Middle Bronze Age (2000-1500 B.C.) (Morley n.d.). The primary mound must have been built by the Early Bronze Age. The cremated human bone that had been deposited within the secondary mound was accompanied by fragments of pottery that belonged to the Deverel-Rimbury culture (Morley n.d.). This style of pottery dates to the Middle Bronze Age period, 1500-1300 B.C. and provided a *terminus ante quem* for the building of the second mound (Morley n.d.).

All of the abraded pottery sherds recovered from the domestic refuse that partially constituted the secondary mound dated to the Early to Middle Bronze Age (2000-1500 B.C.) (Morley n.d.). The residual nature of these pottery sherds meant that they could not be used to date the construction of the second mound (Morley n.d.). Construction of the barrow most likely occurred over the Early and Middle Bronze Age, but it was difficult to say whether the individuals found there died and were buried during this period (Morley n.d.). The deviant attitude of the extended skeleton suggested that this individual represented a later post-Roman interment (Morley n.d.). However, the extended skeleton was recovered from underneath the alluvial sediments, at a similar burial depth to all of the other remains from the mound. These observations indicated that this skeleton represented a rare extended Later Prehistoric interment (Morley n.d.).

The articulated flexed skeleton found towards the east of the site in the space between the mound and the bank was recovered from the inundation layers (Morley n.d.). This sediment demonstrated more frequent instances of Late Bronze Age/Early Iron Age pottery (Morley n.d.). This skeleton most likely represented a Late Bronze Age/Early Iron Age interment on the bank of the inundated round barrow (Morley n.d.). The position of the body suggested that it could have been buried shallowly on the edge of the bank or placed on the ground surface where it was buried by silt (Morley n.d.). The position of the rest of the burials within the original mound and bank suggested that they pre-dated the Late Bronze Age/Early Iron Age inundation (Morley n.d.). If it was assumed that the two types of interment, cremated and unburnt inhumation, represented two distinct phases of activity, then the earliest period that inhumation could have begun was after the insertion of the Deverel-Rimbury cremation in the Middle Bronze Age (Morley n.d.). However, funerary processes in the Bronze Age are not always conveniently phased. Rites of cremation and unburnt inhumation in have appeared contemporaneously at Bronze Age sites (Darvill 2010). The articulated inhumations could have dated to any time between the Early and Late Bronze Age.

Osteological analysis of the bones from Neat's Court suggested that a selection of the articulated burials had been subjected to unusual *post mortem* treatment (Deter & Barrett 2009). All of the skeletons from the mound, plus one recovered from the space between the barrow and the bank, demonstrated orange, brown, black and grey discolouration concentrated at the epiphyses of long bones (Deter & Barrett 2009). Red/brown discolouration and fracturing at the enamel-cementum junction was observed within the dentition of the same individuals. These features were not observed within the bones of the later burial. The discolouration of the bones were consistent with each body having been exposed to low levels of burning (Deter & Barrett 2009). Most of these skeletons were surrounded by ash *in situ* (Morley n.d.). Ash was found directly adhering to some of the remains, but the surrounding soil was not discoloured, which suggested that burning had not taken place in or around the graves (Morley n.d.).

All of the skeletons apart from the later individual were surrounded by London Clay mixed with large quantities of domestic refuse including charcoal, bone and pottery (Morley n.d.). London Clay is a fine-grained, marine geological formation that is distributed across the southeast of England. It is a very dense substrate, and the pure substance can be watertight (Hight *et al.* 2003). It was possible that the density of this substrate produced an anoxic or hypoxic burial environment within the Neat's Court barrow. However the large quantities of extraneous domestic material that were included within the reworked clay would have broken up the sediment and allowed it to retain a degree of aeration.

Palaeoenvionmental reconstructions of the area suggested that the barrow would have lain close to the coast throughout the Bronze Age. The elevation of the bank and the mound would have ensured that the bodies remained dry during decomposition (Morley 2012, personal communication). The burial conditions within the Neat's Court Barrow would probably have been rendered anoxic by the estuarine inundations that eventually covered the monument (Morley n.d.). The length of time that passed between burial (Early-Middle Bronze Age) and these inundations (Late Bronze Age/Iron Age) meant that that it was unlikely that anoxia would have interfered with bodily decomposition. There was no unusual survival of organic material or soft tissue. The burial sediments and skeletons from Neat's Court did not meet the criteria for being classified as having originated from anoxic sediments.

The bones from Neat's Court were held by Swales and Thames Archaeology. Permission to sample the remains was granted by Geoff Morley. The fragmentary and incomplete nature of the Neat's Court remains meant that all of the skeletons could be sampled for thin section

analysis without having to cut a fragment from a whole bone. Fragments of the anterior left femoral mid-shaft were obtained from all six of the articulated skeletons. A thin section was also produced from a fragment of the disarticulated humerus that was recovered from the mound surface. Skeletal part representation amongst the other remains confirmed that this bone originated from a discrete individual (Deter & Barrett 2009). Remains that variably showed signs of having been exposed to heating were included. All of the Neat's Court individuals were sampled specifically for the current project using the techniques expounded in the Methodology chapter (Table 4.20). The bones from this site were fragile and had to be embedded in resin before thin sections could be cut.

Specimen	Age	Sex	Element	Articulation	Position	Burning
SK 2326	Adult	Unknown	Humerus	Disarticulated	-	None
SK 2545	45+	Male	Femur	Articulated	Flexed	Yes
SK 2611	17-25	Male	Femur	Articulated	Extended	Yes
SK 2614	17-25	Female	Femur	Articulated	Flexed	Yes
SK 2635	45+	Male	Femur	Articulated	Flexed	Yes
SK 2666	Adult	Unknown	Femur	Articulated	Flexed	None
SK 2673	17-25	Male	Femur	Articulated	Flexed	Yes

Table 4.20: Catalogue of the human remains that were sampled from the Neat's Court assemblage.

4.1.2.12 South Dumpton Down, Broadstairs, Kent, U.K.

South Dumpton Down is a small area of farmland located at South Cliff in Dumpton, Broadstairs in Kent, U.K. (Figure 4.43). Excavation of the site was carried out between 1992 and 1994 by the Trust for Thanet Archaeology in response to potential development (Perkins 1994). The earliest phase of activity consisted of a round barrow surrounded by a ring ditch (Perkins 1994). A group of three inter-cutting pits were found underneath the centre of this barrow. These pits contained human remains representing at least seven individuals (Perkins 1994: 3) (Figure 4.44). Only two of these skeletons were complete and articulated. The other five skeletons were mostly complete but partially articulated (Perkins 1994: 3). The skulls were missing from most of these skeletons. The persistent loss of the skulls suggested that they had been purposefully removed after the soft tissue had been lost (Perkins 1994: 3). The sequence of deposition and the loss of skeletal elements inferred that these burials represented a sequence of successive inhumation (Perkins 1994: 3). Disturbance of the previous burials was caused by their movement to accommodate the new bodies as well as by the intentional retrieval of skeletal parts (Perkins 1994: 3).

Figure 4.43: Map of the location of South Dumpton Down.

This Image/Figure has been removed, as permissions to print/distribute were not obtained.

Figure 4.44: Plan of the skeletons recovered from the three pits located beneath the South Dumpton Down round barrow (Perkins 1994: 8).

The pits were not large enough to accommodate all of the individuals separately, and most of the skeletons overlay one another. Each burial was separated by a thin layer of soil. All of the burials had originally been deposited in a flexed posture, although the extent of their flexion varied (Perkins 1994: 6). The attitudes and partial articulation of the skeletons suggested that they had been disturbed before the soft tissue had decomposed. The skeleton of Burial 7 was found pressed up against the wall of one of the pits, with its legs lying parallel to and up against the torso (Perkins 1994: 6). It was possible that that the body had been originally placed in this position, although the severity of flexion would have been difficult to achieve on a fresh corpse. The position of the body was consistent with partially-decomposed remains having been pushed to one side of the grave to accommodate new burials.

A later pit had been dug into the eastern segment of the barrow ring ditch. This pit contained the remains of two articulated individuals deposited in opposing orientations (Perkins 1994: 6). A disarticulated mandible from a third individual was also recovered from this pit. The two articulated skeletons lay in contact with each other but had not been disturbed. There was no evidence to suggest that the pit had been cut more than once, and so it was likely that these bodies represented a double burial (Perkins 1994: 6). Another deeper pit was located around two metres east of the eastern ring ditch segment. This pit was found to contain a flexed articulated skeleton (Perkins 1994).

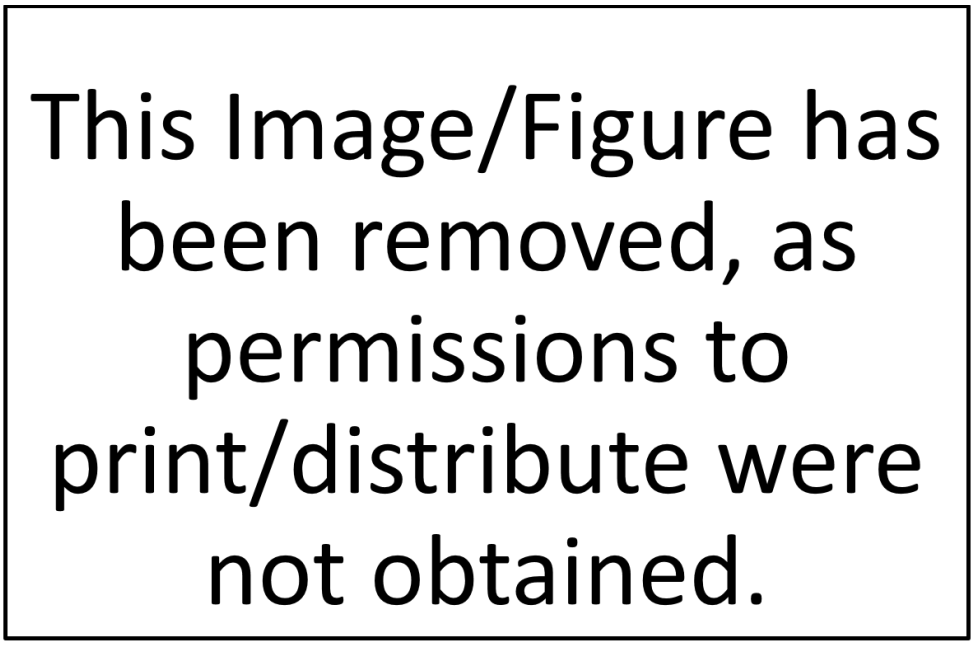

Figure 4.45: Plan and section drawings of the South Dumpton Down round barrow with primary and satellite deposits (Perkins 1994: 7).

The next phase of funerary activity was associated with two rectilinear enclosures formed by palisade trenches. Posthole arrangements within the enclosure corresponded with hut sites or similar structures, which suggested the presence of a settlement (Perkins 1994). A series of forty-six pits were found scattered within and outside the palisaded settlement (Perkins 1994; 1995). The original function of these pits could not be determined, but all had been backfilled with a mixture of midden material, burnt soil and ashes. One of the largest pits included a single articulated flexed human burial accompanied by an iron belt buckle and a bone pin (Perkins 1994: 12). Three more of the pits found across the settlement contained articulated human burials. These three contexts were not discussed in detail within the site report, although the attitudes of the bodies gave the impression that the individuals had been thrown into their contexts rather than deposited in an ordered fashion (Perkins 1994; 1995).

The earliest phase of activity at South Dumpton Down could be dated broadly by the artefact evidence. A food vessel was recovered from the chalk floor of Pit B, underneath the rib cage of Burial 2 (Perkins 1994: 6). A Beaker-style pot was found high in the fill of Pit C associated with Burial 4 or Burial 6. The style of both vessels dated to the Early Bronze Age (Perkins 1994: 6). Burials 1, 3 and 5 were radiocarbon dated (Ambers & Bowman 1998). The femur of Burial 1 was dated twice, producing dates of 1736-1461 cal. B.C. (95% confidence) and 2189-1882 cal. B.C. (95% confidence) respectively (Perkins 1994). These dates were incompatible with one another, which the radiocarbon lab attributed to contamination (Perkins 1994; Ambers & Bowman 1998). Tests of the femora associated with Burial 5 and Burial 3 produced radiocarbon dates of 2010-1696 cal. B.C. (95% confidence) and 2030-1754 cal. B.C. (95% confidence) (Perkins 1994; Ambers & Bowman 1998). The radiocarbon dates of supported an Early Bronze Age date for the skeletons from the South Dumpton Down barrow (Perkins 1994).

No radiocarbon dates were obtained from the skeletons associated with the third phase of activity at South Dumpton Down. The rectilinear enclosure was aligned with features of the Middle-Late Bronze Age enclosure (Perkins 1994). The pits that littered the enclosure contained quantities of domestic and industrial refuse including pottery and iron slag (Perkins 1994; 1995). These artefacts dated to the Early Iron Age and indicated that the associated skeletons had been deposited during this time period (Perkins 1994: 12).

The Bronze Age inhumations recovered from the three pits beneath the round barrow had been buried beneath a light red-brown loam (Perkins 1994: 5). Loam contains concentrations of silt and clay, and is likely to retain moisture more effectively than gravel or sandy contexts (Janaway 1996). However, this burial substrate would still have been aerated and free-draining

(Janaway 1996). These burial soils would not have promoted anoxic conditions through retention of water. The four inhumations collected from the Iron Age pits were interred with deposits of midden material, ashes and burnt soil (Perkins 1994: 12). The coarseness of these deposits would have ensured that the burial contexts remained well aerated and free-draining (Janaway 1996). There was no significant preservation of organic grave goods from any of the phases. There was no evidence to suggest that any of the burials from South Dumpton Down had decomposed within an anoxic environment. However the disarticulation of some of the Bronze Age skeletons suggested that the bodies may have been deposited elsewhere before being interred underneath the round barrow (Perkins 1994).

The skeletons from South Dumpton Down were held at The University of Kent. Permission to sample the remains was obtained from Dr. Patrick Mahoney. Six of the individual skeletons recovered from South Dumpton Down were sampled for thin section analysis. Sampling was undertaken specifically for the current project and followed the processes outlined in the Methodology chapter. All samples were taken from the left femur. The first samples were taken from the Early Bronze Age skeletons 2, 5, 6 and 7. The articulation of these skeletons ranged from almost complete to mostly disarticulated, including most stages in-between. A sample was also taken from one of the articulated skeletons from the flat grave inserted outside of the eastern section of the ring ditch that surrounded the round barrow. The individuals buried in this part of the site had not been dated directly, although their association with the barrow, the orientation and attitude of their burial and their stratigraphic relationship to later phases of activity suggested that they dated to the Early or Middle Bronze Age (Perkins 1994). The last sample was taken from a skeleton recovered from a large pit within the Iron Age settlement (Table 4.21). None of these skeletons had been aged or sexed using osteological techniques, although it was clear by bone size and state of epiphyseal fusion that all were adult. All of the samples from this site were thin-sectioned without having to be embedded.

Specimen	Date	Context	Articulation
Burial 6	Bronze Age	Round Barrow	Partially Articulated
Burial 10	Bronze Age	Flat Grave	Disarticulated
Burial 13	Iron Age	Pit	Articulated
Burial 5	Bronze Age	Round Barrow	Articulated
Burial 2	Bronze Age	Round Barrow	Partially Articulated
Burial 7	Bronze Age	Round Barrow	Partially Articulated

Table 4.21: Catalogue of the human remains sampled from the South Dumpton Down assemblage.

4.1.2.13 Suddern Farm, Middle Wallop, Hampshire, U.K.

Suddern Farm lies to the west of the Danebury hillfort, just outside of the village of Middle Wallop (Figure 4.46). The site was excavated in 1991 and 1996 as part of the Danebury Environs Project run by English Heritage and the University of Oxford (Cunliffe & Poole 2000). The survey of the earthworks revealed that the site consisted of a medium-sized double or treble-ditched enclosure measuring 2.2 hectares (Cunliffe & Poole 2000). The 1991 excavations were concerned with the excavation of this enclosure. The pottery found during these excavations was of the same style as that recovered from within the Danebury hillfort and confirmed the Iron Age occupation (Cunliffe & Poole 2000). The Danebury ceramic phases were used to date the sequences at Suddern Farm and no radiocarbon dating was undertaken (Cunliffe 1983; Cunliffe & Poole 2000). The exact sequence of the development was difficult to ascertain, as dateable finds were more commonly recovered from accumulated silts rather than the bottom of the ditches (Cunliffe & Poole 2000).

Figure 4.46 Map of the location of Suddern Farm.

The site began as a Late Bronze Age single-ditched enclosure consisting of that was utilised into the Early Iron Age (Cunliffe & Poole 2000) (Figure 4.47). Excavations of the ground inside the enclosure revealed patterns of post holes and pits similar to those observed within the residential areas of the Danebury hillfort (Cunliffe 1983; Cunliffe & Poole 2000). This period of occupation was characterised by distributions of huts interspersed by large storage pits (Cunliffe & Poole 2000). The artefacts suggested the site was occupied from the Early to Middle Iron Age (Cunliffe & Poole 2000: 65).

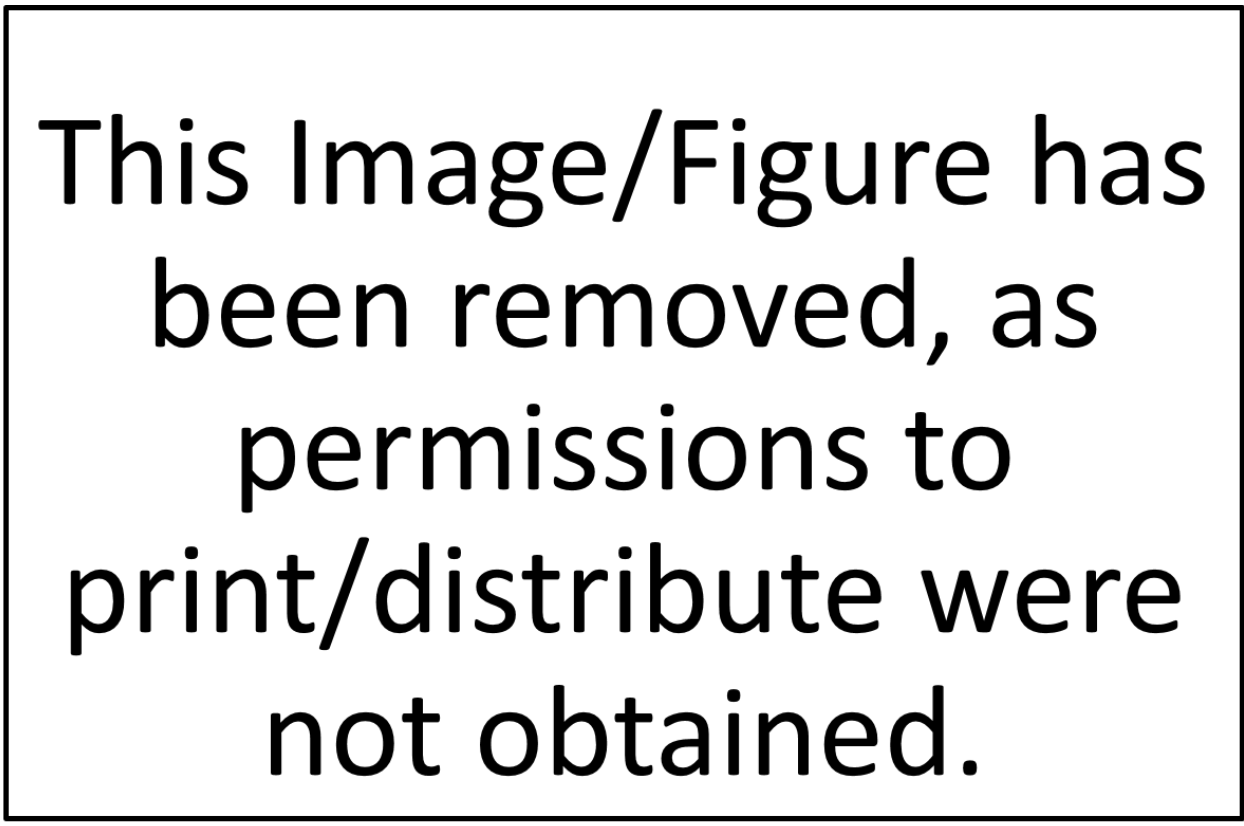

Figure 4.47: Plan of the Suddern Farm earthworks along with the location of the quarry cemetery (Cunliffe & Poole 2000:14)

Substantial human remains were only recovered from two contexts within the ditched enclosure (Cunliffe & Poole 2000: 21). A partial skeleton that was missing its arms and lower legs was excavated from one of the pits associated with ceramic phase 8 (Cunliffe & Poole 2000: 21). An incompletely-cremated partial skeleton was recovered from another storage pit (Cunliffe & Poole 2000: 21). The latter skeleton was associated with quantities of burnt animal

bones and domestic debris. Isolated disarticulated human bones and bone fragments were recovered from another four pits associated with Early Iron Age deposits (Cunliffe & Poole 2000: 21).

The 1996 excavations focussed on a three-ditch linear earthwork that was located to the southwest of the circular ditched enclosure. These excavations located a quarry that was cut by the outer ditch. Investigations of the quarry revealed that it had subsequently been used as a cemetery (Cunliffe & Poole 2000). Human remains representing a minimum number of sixty individuals were excavated from this burial ground (Cunliffe & Poole 2000: 152) (Figure 4.48). The majority of the skeletons had been buried in articulation within discrete purpose-built graves (Cunliffe & Poole 2000: 152).

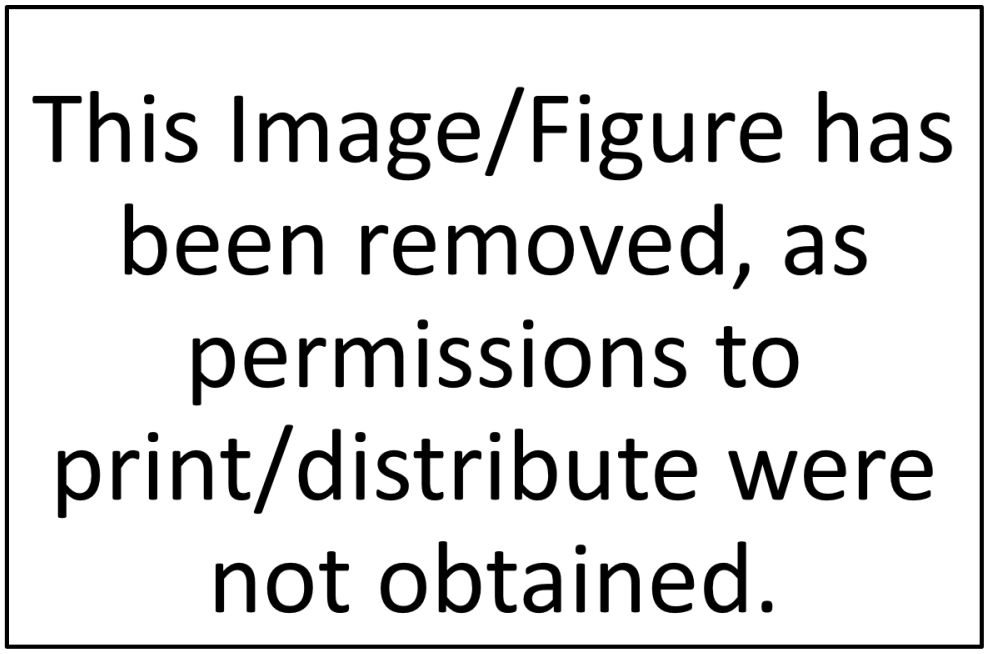

Figure 4.48: Plan of the Suddern Farm Quarry cemetery (Cunliffe & Poole 2000: 153).

The grave pits occasionally penetrated down to the chalk bedrock, although the majority had been interred within the quarry spoil, which mostly consisted of chalk rubble and natural silt (Cunliffe & Poole 2000: 166). Skeletons were recovered in various stages of articulation and often accompanied by partial remains of other individuals (Cunliffe & Poole 2000: 166). Analysis of the grave cuts suggested that previous burials had not been respected by new interments. Accompanying disarticulated material most likely represented charnel bone that had been redeposited after being disturbed by new grave cuts (Cunliffe & Poole 2000: 168).

Most of the disturbed skeletons demonstrated high levels of anatomical articulation amongst separated elements, which suggested that many of them were disturbed soon after death, before the connective tissue had decomposed (Cunliffe & Poole 2000: 168). The absence of skulls from many of the disturbed burials emphasised an interest in this skeletal element that was also noted at Danebury (Cunliffe & Poole 2000: 166).

All of the skeletons from the Suddern Farm cemetery were recovered in variably flexed postures (Cunliffe & Poole 2000: 166). There was a dichotomy between loosely and tightly flexed attitudes, which suggested that some of the bodies may have been bound (Cunliffe & Poole 2000: 166). Two of the burials were recovered with possible grave goods; an iron nail and an iron fibula respectively. One of the skeletons had been gnawed by rodents. These remains were accompanied by the skeleton of a mouse, and it was likely that the observed alterations had been produced by burrowing rodents (Cunliffe & Poole 2000: 167).

The burial sediments were composed of chalk rubble silts that derived from the erosion of the graves (Cunliffe & Poole 2000). The build-up of silts within many of the graves indicated that some of them may have been left open for an extended duration (Cunliffe & Poole 2000: 166). The burial environments would have remained aerated throughout the stages of bodily decomposition. The chalk rubble was coarse as well as free draining and would not have encouraged anoxia through retention of water. There was no preservation of organic remains that may have indicated previous anoxic conditions. There was no evidence that the environmental conditions at Suddern Farm would have affected bodily decomposition.

The human remains excavated from the Suddern Farm cemetery were held by the Hampshire Museum Service. Permission to sample the bones was granted by Dave Allen. It was deemed useful to sample some of the human material from Suddern Farm for thin section analysis to complement the bones sampled from the Danebury hillfort. Occupation of Suddern Farm and Danebury was contemporary and remains from both sites were buried within similar environments. However, Cunliffe & Poole (2000: 168) argued that the two assemblages represented discrete funerary traditions. The inclusion of the Suddern Farm remains potentially increased the variability of treatment captured by the Iron Age assemblages.

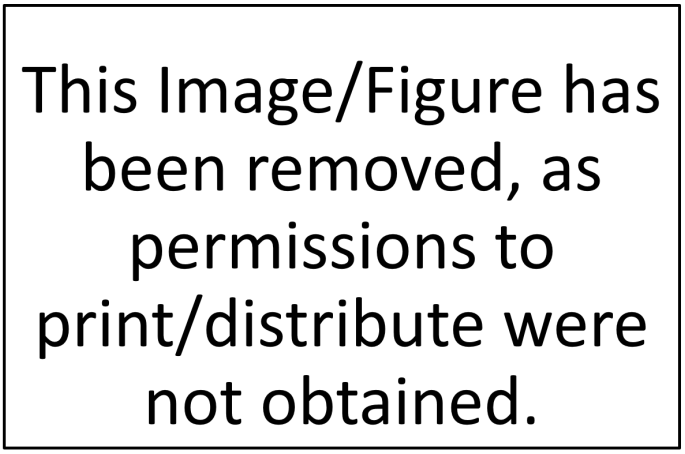

Figure 4.49: Plans of the burials from Suddern Farm that were sampled for this project (Cunliffe & Poole 2000: 155).

Two partial skeletons were sampled from Suddern Farm. Both of these deposits were recovered from the same pit, with one lying on top of the other (Figure 4.49). These skeletons were sampled to examine the differences or similarities in diagenesis between remains that had been buried in the same environment (Table 4.22). The skeleton of a young female was found lying on its back in a tightly flexed position. The skull and lower right leg of this individual were missing. An adult male skeleton lay below the female in a tightly-flexed, prone position. The skull of this individual was missing, and one of the legs had been disarticulated. The higher levels of disarticulation within the female skeleton suggested that it represented an earlier deposit that was disturbed by the deposition of the adult male (Cunliffe & Poole 2000: 167). The conspicuous absence of the skulls of both individuals suggested that there had been intrusive recovery of select bones after the soft tissue had decomposed. Both of the samples used for thin section analysis were taken from the left femur. The thin sections were produced specifically for this project using the procedures outlined in the Methodology chapter. The sections could be cut without them having to be embedded.

Specimen	Age	Sex	Position	Articulation
C19	~16	Female	Flexed supine	Partially Articulated
C20	~30	Male	Flexed prone	Partially Articulated

Table 4.22: Catalogue of the human remains sampled from the Suddern Farm assemblage.

4.1.2.14 Windmill Fields, Ingleby Barwick, Stockton-On-Tees, County Durham, U.K.

Windmill Fields is an area of the Ingleby Barwick housing development that lies between the towns of Eaglescliffe, Thornaby and Yarm, in the borough of Stockton-On-Tees, in Country Durham. In 1996, human remains were discovered in the spoil of construction work on a new road within the Windmill Fields development. Exploratory excavations by Tees Archaeology discovered that these remains originated from two single flexed articulated burials (Sk. 1 & Sk. 2) (Annis *et al.* 1997). Further exploration of the area revealed an oval pit that was defined by dark staining (Annis *et al.* 1997: 4). Excavation of this feature revealed the remnants of a wooden cist that contained two groups of disarticulated human bones separated by a thin layer of soil (Annis *et al.* 1997: 5). These bone piles mostly consisted of skulls and long bones, but also included a pelvis (Annis *et al.* 1997: 5).

Figure 4.50: Map of the location of the Windmill Fields site in Ingleby Barwick.

Another single grave was identified within the cut for the road (Annis *et al.* 1997). This grave contained the remains of a flexed articulated skeleton accompanied by a stone mace-head (Sk 5) (Annis *et al.* 1997: 5). Further excavations revealed two more single graves (Annis *et al.* 1997: 7). The first contained the remains of a single skeleton that had been disarticulated by

modern disturbance (Sk. 7). The other consisted of an articulated skeleton that had been placed in a flexed posture on its right side (Sk. 6) (Annis *et al.* 1997: 7). Sk. 6 had been richly adorned with various grave goods (Annis *et al.* 1997: 7). The long bones and skull of a second individual had been inserted into the fill of this grave. It was unclear whether this secondary deposit represented a previous burial that had been removed to accommodate the new skeleton or a deliberate deposit of curated disarticulated remains (Annis *et al.* 1997: 7). Post-excavation analysis revealed that both Sk. 5 & Sk. 6 were also accompanied by bone from separate individuals (Annis *et al.* 1997).

Figure 4.51: Plan of the excavated features at the Ingleby Barwick site (Annis et al. 1997: 8)

Ploughing and development had removed the upper parts of all of these features and so their relative stratigraphic relationships could not be discerned. However, the pit that included the wooden cist was notably deeper than the single graves (Annis *et al.* 1997: 7). The human remains represented a minimum number of eleven individuals (Annis *et al.* 1997; Anderson 1998). The disarticulated bones from the wooden cist were examined for signs of animal alteration, cut marks and weathering (Anderson 1998). The cortical preservation of the bones

was too poor to say whether these features were manifest (Anderson 1998). The bones from the cist demonstrated erosion indicative of water movement (Anderson 1998). This observation indicated that the bones had lain within the empty cist, allowing water to drip directly onto the assemblage (Anderson 1998). It was probable that the bones had not been buried immediately but had lain on the floor of the cist for a time until they were buried by natural deposition or human activity (Annis *et al.* 1997).

The mace-head that was found with Sk. 5 as well as the grave goods that adorned Sk. 6 were dated typologically to the Late Neolithic/Early Bronze Age Beaker period (Annis *et al.* 1997: 16). This assertion was supported by fragments of Beaker pottery found near the burial of Sk. 5 (Annis *et al.* 1997: 3). Bones from all of the single articulated burials as well as the disarticulated individuals represented in the wooden cist were radiocarbon dated. At the time that the remains were sampled in 2008, the radiocarbon dates combined with the funerary traditions suggested that there had been three periods of interment consisting of Late Neolithic disarticulated cist deposits, Early Bronze Age unfurnished articulated burial and Early/Middle Bronze Age furnished articulated burial (Rowe 2008 personal communication). The disarticulated bones from the cist were considered to be Neolithic for the purposes of the present study.

Later Bayesian modelling recognised only two probable phases of activity, although there was some overlap (Rowe 2012, personal communication). The results of this modelling were made known to the author after the initial analysis of the thin sections had already taken place. The individuals represented by Sk 1, Sk 2 and Sk 7 all died around the same time in the Late Neolithic/Early Bronze Age period and represented the first phase of interment at the site, consisting of deposition of disarticulated bones in the wooden cist and unfurnished articulated inhumation (Rowe, personal communication 2012). The second phase of activity consisted of furnished burials and took place 60-220 (68% confidence) or 0-250 (95% confidence) years later in the Early to Middle Bronze Age. All of the remains from Ingleby Barwick were likely to be Bronze Age. The repercussions of the incorrect allocation of the cist material to the Neolithic is addressed in later chapters.

All of the skeletons were recovered from free-draining gravel soils (Annis *et al.* 1997). The coarseness of these soils would have ensured consistent aeration (Janaway 1996). The soils would not have retained water efficiently to have promoted frequent episodes of anoxia through waterlogging. The sediments were unlikely to have interrupted putrefaction, although it should be noted that the bodies represented by the disarticulated bones from the cist may

have decomposed within separate environmental conditions (Annis *et al.* 1997). There was no survival of organic grave goods that may have indicated a previous anoxic environment (Annis *et al.* 1997). The wooden cist survived only as staining in the soil.

Four of the skeletons had been sampled by the author for use in a Masters project (Booth 2008). The remains were held by Tees Archaeology, and permission to sample them was granted by Peter Rowe. These thin sections were still available in the collections at the University of Sheffield Department of Archaeology. The sampling strategy for Booth's (2008) project was focussed on obtaining a representative sample of funerary treatment and different phases of activity. These aims were analogous to those of the current project (Booth 2008). Thin sections had been produced from four of the individuals (Table 4.23). All of the sections were sampled from left femora.

The thin sections had been produced using the techniques explained in the Methodology chapter. The samples had not required embedding and were mounted using Euparal resin. The thin sections had been previously assessed by the author using the OHI for a Masters dissertation (Booth 2008). However, reassessment of the thin sections was required in order for further diagenetic variables to be recorded. OHI had been mistakenly recorded using the system of Hedges *et al.* (1995) rather than the updated Millard (2001) system during work for the Masters project (Booth 2008). OHI had only been recorded for the thin sections as a whole and had not included an assessment of the constituent parts of each section separately. The OHI scores of the Ingleby Barwick remains were rerecorded in order to ensure that they were consistent with the scores allocated to the rest of the samples used in the current study.

Specimen	Age	Sex	Articulation	Radiocarbon Date (cal. B.C., 95% confidence)
Sk. 2	Young Middle Adult	Male	Articulated	2200 - 1970
Sk. 3	Middle Adult	Male	Disarticulated	2400 - 2040
Sk. 5	Middle Adult	Male	Articulated	1740 - 1530
Sk. 6	Young Middle Adult	Female	Articulated	2030 - 1885

Table 4.23: Catalogue of the human remains sampled from the Ingleby Barwick site.

4.1.2.15 Whitwell Quarry, Bolsover, Derbyshire, U.K.

The Whitwell limestone quarry is located between the villages of Creswell and Whitwell in Derbyshire. The site was discovered during a survey of karst features and fissures that was undertaken on the active face of the quarry. The excavation was conducted by Bassetlaw Heritage Project and researchers from the Creswell Crags Museum between 1988 and 1989 in advance of extension of the limestone quarry. The excavations uncovered a portion of a trapezoidal long cairn that held the remains of a single articulated individual and a deposit of disarticulated, comingled bones that represented the remains of at least sixteen people (Vyner & Wall 2011).

Figure 4.52: Map of the location of Whitwell Quarry.

The first phase of the site consisted of an east-west aligned linear deposit of disarticulated bones between two wooden posts. Bones from similar parts of the body were often found lying close to one another without retaining correct anatomical articulation (Vyner & Wall 2011: 10). The posts and the bones were surrounded by intermittent lines of limestone blocks. The bone deposit was defined by straight edges before the lines of limestone blocks, which suggested that the remains had been contained within a timber mortuary structure flanked by

the limestone kerb (Vyner & Wall 2011: 10). The human remains were recovered in contact with the old ground surface, although it was probable the mortuary structure originally included a wooden floor (Vyner & Wall 2011: 10).

A single articulated inhumation of a sixteen or seventeen year old female was found seven metres to the south of the linear mortuary deposit (Vyner & Wall 2011: 12) This skeleton had been placed directly on the ground surface between two large sub-circular pits. The burial was surrounded by limestone slabs, but the excavators could not discern whether these slabs had been deposited with the burial or were related to the later cairn (Vyner & Wall 2011). The nature of the collapse of the cairn material that had surrounded the articulated burial suggested that the body had lain within a timber box (Vyner & Wall 2011: 12).

The initial part of the stone cairn was constructed over the single articulated individual (Vyner & Wall 2011: 13). The presence of mollusc shells within the skull of this skeleton suggested that the body had been accessible during the period of its decomposition, and that construction of the cairn must have post-dated skeletonisation (Vyner & Wall 2011: 10). A limestone oval cairn was constructed on top of the timber funerary box. This cairn was surrounded by a low limestone wall. A second phase of construction involved the erection of a new wall and the infilling of space between the cairn and this new structure with limestone slabs and stones.

The two mortuary deposits were joined together through the construction of a large trapezoidal limestone cairn (Vyner & Wall 2011). The wooden structure that surrounded the primary linear deposit of disarticulated human bone was removed and replaced by rubble and limestone (Vyner & Wall 2011: 14). The cairn was surrounded with a low dry stone wall. Further disarticulated and comingled remains were recovered from above the intermittent layers of limestone deposited during the construction of the cairn, which signified a second phase of deposition within the linear mortuary deposit (Vyner & Wall 2011). A linear passage was constructed within the trapezoidal cairn that connected the mortuary chamber to a northeast entrance. The construction of this entrance ensured constant access to the linear mortuary deposit (Vyner & Wall 2011: 8) (Figure 4.53). Deposition within the Whitwell tomb was ended when the entrance was blocked by a mixture of limestone slabs and rubble (Vyner & Wall 2011).

Fragments of pottery were recovered from throughout the Whitwell cairn associated with periods of construction and mortuary deposition. All of the fragments belonged typologically

to the Neolithic Carinated Bowl tradition (Vyner & Wall 2011: 29). Three radiocarbon dates were obtained from two of the bones recovered from the linear mortuary deposit and one from the isolated articulated individual. These tests produced radiocarbon dates of 4310-3770 cal. B.C. (95% confidence), 4370-3980 cal. B.C. (95% confidence) and 4050-3710 cal. B.C. (95% confidence) respectively (Vyner & Wall 2011: 33). These radiocarbon dates were within the Neolithic but were anomalously early (Vyner & Wall 2011: 33).

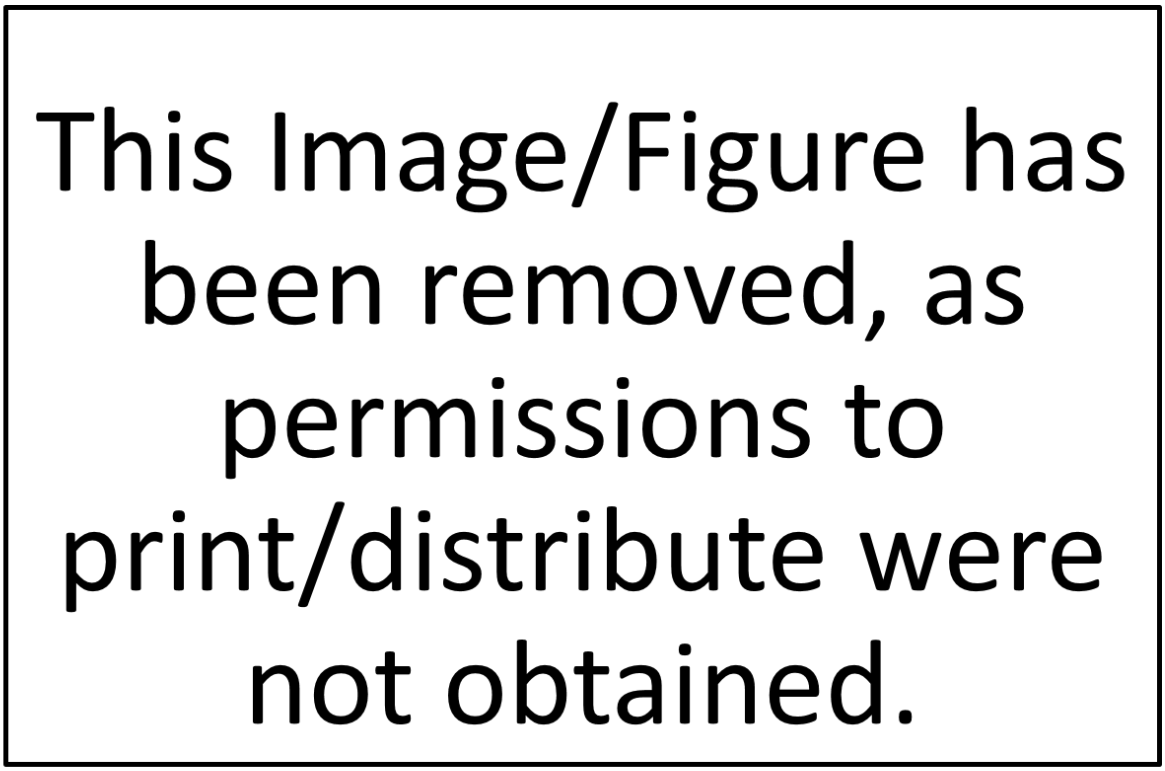

Figure 4.53: Plan of the excavated part of the long cairn at Whitwell with distribution of pottery types (Vyner & Wall 2011: 8).

A second round of radiocarbon dating undertaken between 2000 and 2005 discovered that these early dates were unreliable due to contamination of the bone by a PVA consolidator (Vyner & Wall 2011: 33). The second round of analysis redated the bone samples that had been taken previously and analysed further bone fragments representing twelve individuals from the linear mortuary deposit. Radiocarbon dates were also acquired from hazelnut shells and animal bones. Bayesian modelling of the dates combined with the assumption that the majority of individuals had been interred within the cairn soon after death were used to provide specific date ranges for each phase of interment (Vyner & Wall 2011: 33). The results suggested that the deposition of human remains within the wooden structure of the linear

mortuary deposit began between 3790 and 3710 cal. B.C. (95% probability), and that this phase of deposition continued right up until the removal of the wooden structure and the construction of the stone cairn in 3720-3650 cal. B.C. (95% probability) (Vyner & Wall 2011: 36). The single inhumation was probably interred during the initial period of the linear mortuary structure in 3760-3650 cal. B.C. (95% probability) (Vyner & Wall 2011: 36). The first bones were deposited within the new mortuary structure in 3820-3720 cal. B.C. (95% probability) and mortuary activity continued until 3630-3540 cal. B.C. (95% probability) (Vyner & Wall 2011: 36). These results indicated that all individuals represented within the cairn had died over two centuries within the Early Neolithic (Vyner & Wall 2011: 36).

The spatial patterning and representation of skeletal elements around the Whitwell cairn were analysed in order to deduce what kind of funerary treatment was likely to be responsible for the assemblage (Figure 4.54). Identification of antimeres and bone fragment matches helped to establish the extent to which the bones of a single individual had been distributed throughout the cairn. This analysis found that skeletal elements were often closely grouped by anatomical proximity (Vyner & Wall 2011). These observations suggested that whole bodies had been interred within the cairn (Vyner & Wall 2011: 87). These remains were then disarticulated by subsequent disturbance and movement of elements or partial bodies. There was a low representation of the small bones of the hands and feet amongst the assemblage as a whole. Similar loss of small bone has been associated with secondary deposition of remains (Mays 2008). However, it was likely that the small bones of the individuals interred within the Whitwell cairn had been lost as a result of chemical erosion by the surrounding sediment (Vyner & Wall 2011: 91).

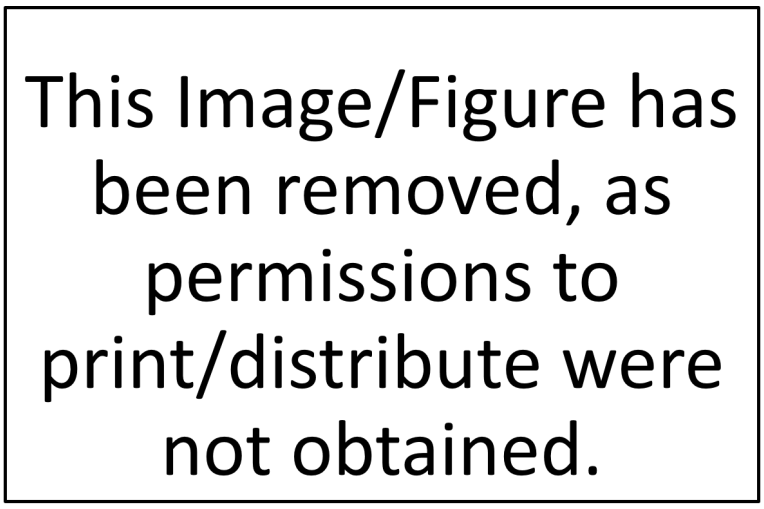

Figure 4.54: Plan of the linear mortuary deposit at Whitwell cairn (Vyner & Wall 2011: 22).

The soils that surrounded the remains consisted of calcareous loess (Vyner & Wall 2011). Loess is silty and free-draining. If the bodies had lain inside the cairn it was probable that they had decomposed within an empty space rather than sediment (Vyner & Wall 2011). If the remains had become buried at an early stage, it was unlikely that the soils would have affected bodily decomposition through anoxia. There was no reason to believe that the cairn or mortuary boxes were flooded or waterlogged for significant periods of time after deposition, and the disarticulation of the remains combined with the presence of the passageway suggested that interred bodies were freely accessible during and after soft tissue decomposition. There was no significant survival of organic remains that may have betrayed a previous anoxic environment.

It was hoped that sampling would encompass the disarticulated remains from the linear mortuary deposit as well as the articulated burial from the oval cairn. Unfortunately the articulated burial was on display at the Creswell Crags Museum at the time of sampling and could not be accessed. All other bones were available within the collections at the University of Sheffield Department of Archaeology. Five disarticulated left femora from the linear mortuary deposit were sampled (Table 4.24). These samples represented all of the left femora that were available from the site. Some of the femora were fragmented, and each femoral fragment was checked against the rest to ensure that no two could have originated from the same bone. The samples were taken specifically for the current project using the techniques outlined in the Methodology chapter. The Whitwell samples could be cut without having to be embedded.

Specimen	Age	Sex
740	Adult	Unknown
657	Adult	Unknown
253	Adult	Female
218	Adult	Unknown
630	Adult	Unknown

Table 4.24: Catalogue of the human remains sampled from the Whitwell cairn assemblage.

4.2 SUPPLEMENTARY REMAINS

The remains discussed above were all sampled to be used in a large-scale comparison of levels of diagenesis within human remains recovered from Later Prehistoric and Historical contexts. A small number of supplementary samples were taken from other site assemblages to help

elucidate the relationship between diagenesis and funerary process or justify methodological assumptions. The details of these samples as well as the reasons for their inclusion are provided below.

4.2.1 Mummified Bone

Part of the evidence used to argue that the skeletonised remains recovered from Cladh Hallan had previously been mummified was the arrested pattern of bacterial bioerosion observed within their bone microstructure. This pattern of bioerosion was theoretically consistent with an interpretation of putrefaction having been curtailed by mummification (Aufderheide 2003; Parker Pearson *et al.* 2005; Lynnerup 2007). However, levels of bacterial bioerosion within mummified bone have never been systematically investigated. Investigation of diagenesis within bone from mummified individuals would form a valid part of the current project. Such an investigation would help to establish whether there is a specific signature of bone diagenesis that is consistent with this rite, which would be helpful towards understanding the relationship between bone diagenesis and funerary treatment.

The few histomorphological studies of bone from mummified individuals have found that these specimens remain free from microbial bioerosion (Weinstein *et al.* 1981; Thompson & Cowen 1984; Hess *et al.* 1998). However, mummified individuals that were used in these studies had been preserved in ways that would have affected putrefaction from a point very soon after death. For instance, one of these mummified bone samples originated from the Bronze Age body that was recovered from the Tyrolean Alps (popularly referred to as Ötzi the iceman) (Hess *et al.* 1998). This individual had died at high altitude where the cold temperatures would have ensured that putrefaction bacteria remained inactive (Micozzi 1997; Aufderheide 2003). The dry environment eventually desiccated the soft tissues (Micozzi 1997; Aufderheide 2003).

When mummified remains from all cultures are considered as a whole, it is apparent that many techniques practised by ancient cultures preserved bodily soft tissues inconsistently (Aufderheide 2003; Lynnerup 2007). Perseverance of mummified soft tissue over archaeological timescales is likely to be dependent on a number of variables, such as damage, handling and climatic conditions (Aufderheide 2003; Lynnerup 2007). The survival of preserved soft tissue within a proportion of remains would be dictated by the efficacy of the mummification method in preventing early *post mortem* putrefaction (Aufderheide 2003).

Many mummies have only ever consisted of partially fleshed anatomical elements (Aufderheide 2003; Lynnerup 2007). For instance, rates of soft tissue preservation and skeletal articulation observed amongst the Guanche mummies of Tenerife are extremely variable, despite all of these bodies having been treated similarly (Aufderheide 2003: 162). The patterns of diagenesis observed within bone from mummified remains may have only captured one aspect of variation. It was likely that bacterial bone bioerosion would be more variable within mummified bodies that had undergone some putrefactive loss of soft tissue.

Specimen	State	Date	Publication	Mummification Method	Bone Histology
Peruvian Mummy	Skeleton	A.D. 400-1600	Weinstein *et al.* 1981	Desiccated by burial, wrapping and deep burial in dry, coastal sand.	Perfect microstructure.
Ötzi the Tyrolean 'ice man'	Mummified Body	3300 B.C.	Hess *et al.* 1998	Desiccated by freeze-drying. Cold temperatures prevented putrefaction.	Perfect Microstructure. Species of gut bacteria identified under the periosteum.
Two Utqiagvik barrow mummies	Mummified Body	A.D. 1475	Thompson & Cowen 1984	Desiccated by freeze-drying. Cold temperatures prevented putrefaction.	Perfect microstructure.
Francisco Pizarro	Mummified Body	A.D 1541	Stout 1986	Application of lime (CaO).	Perfect microstructure.
Lindow II & Lindow I/II	Mummified Boy	2 B.C.-A.D. 119	Brothwell & Bourke 1995; Brothwell & Gill-Robinson 2002	Deposition within a sphagnum peat bog.	Well-preserved, but with 'globular pseudopathological points of collagen loss'. Possible accumulations of MFD.
Worsley Man	Partially Mummified Head	A,D, 100	Garland 1995	Deposition within a sphagnum peat bog.	Perfect microstructure.

Table 4.25: Catalogue of mummified bodies whose bone has been subject to histomorphological analysis along with a summary the results of each study.

The aim of the sampling was to obtain bone specimens from bodies that had been variably mummified in order to capture a range of possible signatures. It was hypothesised that bones obtained from remains whose soft tissue had been preserved within only limited success would be more likely to demonstrate putrefactive bioerosion to their internal bone microstructure. Application was made to various institutions to sample mummified bone for thin sections analysis. The destructiveness of the thin section method meant that the chances of obtaining a large number of bone samples from mummified individuals was low. It was likely that retrieval of bone tissue might require removal or destruction of soft tissue. Bone samples were acquired from only two mummified bodies.

4.2.1.1 Yemeni Mummy

Figure 4.55: Map of the approximate origin of the Yemeni mummy that was sampled.

A small fragment of patella that was covered by preserved soft tissue was obtained from Professor Don Brothwell at the University of York. This bone fragment originated from one of the desiccated bodies recovered from the highlands northwest of Sana'a in the Yemen (Figure 4.55). The presence of soft tissue confirmed that the patella had come from a partially

mummified individual. This sample had to be embedded before it could be successfully thin-sectioned.

The patella has not often been subject to histological examination, particularly in studies of bone diagenesis. Therefore comparative thin sections were also produced from two disarticulated patellae of unknown provenance that were available within the University of Sheffield Department of Archaeology's collections. The level of discolouration and cortical erosion on one of these specimens indicated that it had been retrieved from an archaeological context. The fresh appearance of the second patella suggested that it was of a recent origin, probably a dissection room cadaver or retired teaching skeleton. It was expected that the archaeological patella would be informative as to the nature and extent of microbial bioerosion that was possible within this particular skeletal element. The fresh patella would provide an example of unaltered microstructure of this bone. All of these samples were thin sectioned and prepared using the techniques expounded in the Methodology chapter.

4.2.1.2 Derrycashel Bog Body

Figure 4.56: Map of the location of Derrycashel.

In January 2005 partially-mummified human remains were extracted from a peat harvester near the town of Derrycashel, County Roscommon, Ireland (Kelly 2012) (Figure 4.56). The head and feet had been lost to the machinery. Aside from these elements, the body was almost complete. The thorax and upper limbs retained the majority of their superficial soft tissues, although no internal organs could be identified (Kelly 2012). The legs were almost entirely skeletonised. The remains were radiocarbon dated to 1431–1291 cal. B.C., which placed them within the Irish Middle Bronze Age (Kelly 2012). In contrast to Iron Age Irish bog mummies, the Derrycashel remains showed no signs of having been subject to peri mortem trauma (Kelly 2012). The Derrycashel body had been manipulated into a flexed posture, which was a conventional burial position amongst Irish Bronze Age skeletons (Kelly 2012). Iron Age Irish bog bodies are often interpreted in terms of deviant ritual sacrifice and deposition, however the observations outlined above led the excavators to conclude that the Derrycashel body had been formally buried within the peat bog (Kelly 2012). The Derrycashel body provided an opportunity to sample bone from a mummy that demonstrated partial levels of soft tissue preservation resulting from inconsistencies of the method rather than subsequent curation.

The remains of the Derrycashel woman were held at the National Museum of Ireland. Permission to sample the remains was granted by Eamonn Kelly. The left clavicle and a proximal anterior cortical fragment of tibia were collected from the National Museum of Ireland, Dublin and transported to the University of Sheffield Department of Archaeology. Samples from both of these bones were thin sectioned using the techniques outlined in the Methodology chapter. It was pertinent to take samples from both of these bones, as they originated from parts of the body that demonstrated disparate levels of soft tissue preservation. These two bones may have been subject to divergent levels of putrefaction.

4.2.2 Havnø Shell Midden, Jutland, Denmark

The Havnø shell midden is located on the banks of the Mariager fjord in eastern Jutland, Denmark (Figure 4.57). Modern research excavations of the midden by Søren Andersen from the Moesgård Museum began in 2004 and continued up until 2011 (Andersen 2008). The midden was around 100 metres in length, 25-27 metres wide, and had been built up gradually from accumulations of ten to fifteen shell deposits (Andersen 2008). Radiocarbon dates of archaeological material found throughout the midden indicated that the site had been visited

over a long period between 5000 and 3000 cal. B.C. (Andersen 2008: 4). This time period stretched from the Mesolithic middle and younger Ertebølle phases through to the earliest Neolithic Funnelbeaker culture (Andersen 2008: 4). It could not be established if the midden had been visited and constructed continuously throughout this period or whether there had been several punctuated periods of activity (Andersen 2008: 4). The Ertebølle and Funnelbeaker phases could be easily discerned within the midden, as the Neolithic layers held fewer and smaller oyster shells and increased abundances of charcoal and cooking stones (Andersen 2008: 4).

Figure 4.57: Map of the location of the Havnø shell midden

Disparate fragmentary disarticulated human skeletal elements were recovered from various points within the midden phases (Andersen 2008). Radiocarbon dating of human bone samples suggested that disarticulated remains had been deposited throughout the Neolithic and Mesolithic periods (Andersen 2008: 4). The subsoil consisted of a sandy clay, although the human bones were all recovered from within the midden, which was mostly composed of oyster, cockle, mussel and periwinkle shells mixed with domestic refuse, including faunal material, charcoal and cooking stones (Andersen 2008).

Emily Hellewell, a postgraduate researcher from the University of York, was interested in analysing the human bones from the Havnø shell midden using thin section light microscopy to help determine whether funerary processes differed between the Mesolithic and Neolithic phases. There was no consistent representation of particular skeletal elements at the site, and so potential element-specific bone diagenesis could not be controlled (Andersen 2008). Hellewell was still keen to continue with the analysis even after this problem was explained.

The analysis of disparate skeletal elements from this site would be useful to the present study. All bones originated from the same depositional context and analysis of levels of diagenesis could be used supplement the results from the Primary Analysis in establishing whether bone diagenesis varies in characteristic ways within bones from particular parts of the body. If there was no association between skeletal element and diagenesis within the primary study sample and the Havnø remains, then the results from the Havnø samples could be used to infer early taphonomic events. The latitude of the Havnø midden was within the range of central Scotland. The potential effects of climate on bodily decomposition of the Havnø remains would not have differed substantially from those experienced by the bones included in the Primary Analysis.

Eleven human bone fragments from the Havnø midden were sent to the University of Sheffield by Søren Andersen at the Moesgård Museum via Emily Hellewell at the University of York. The aim of the sampling was to obtain a good representation of bone from different parts of the midden. There was also an attempt to sample a wide range of skeletal elements. Samples of replicate skeletal elements were taken to determine whether there were specific signatures of diagenesis associated with different types of bones. It was decided that the sampling should be focussed on long bone shafts to ensure that ratios of cortical and trabecular bone were relatively equal between samples. This strategy was consistent with the primary sample set. This strategy ensured that any variation in bone bioerosion with skeletal element was likely to be associable with anatomy rather than ratio of cortical and trabecular bone. Most elements sampled consisted of long bones, however cranial bones were also included. Cranial bones contain both cortical and cancellous bone, although larger proportions of cranial bones are taken up by cancellous diploë than within long bone shafts. The differences in diagenesis between the cranial and post cranial samples would be closely monitored to discern whether the higher levels of trabeculae may have affected diagenetic parameters.

Bone Number	Bone	Anatomical Area
NSV	Fibula	Limb
QQB	Cranium	Extremity
XPG	Cranium	Extremity
LOU-a	Fibula	Limb
NYA	Ulna	Limb
VNV	Cranium	Extremity
UBQ-b	Phalanx	Extremity
UBQ-a	Metacarpal	Extremity
PCE-a	Clavicle	Axial
THE	Metatarsal	Extremity
OHL-3	Metatarsal	Extremity

Table 4.26: Catalogue of the human remains sampled from the Havnø assemblage along with their anatomical classification.

The disarticulation of the Havnø material combined with the necessity to sample disparate skeletal elements meant that it was possible that bones from a single individual had been sampled more than once. This factor would not affect the ability to determine whether particular skeletal elements demonstrate characteristic signatures of diagenesis, but would have to be considered during any attempts to interpret funerary behaviour. All of the Havnø bones were sampled and thin sectioned using the techniques outlined in the Methodology chapter. None of the samples had to be embedded in resin (Table 4.26).

5 RESULTS – PRIMARY ANALYSIS OF THE WHOLE ASSEMBLAGE

This first results chapter presents the findings of the thin section analysis across the whole study sample in order to identify the factors that influenced different types of bone diagenesis. Identification of these factors were used to determine how different measures of diagenetic change may be used in the reconstruction of taphonomic histories, particularly funerary rites. This chapter is subdivided by each diagenetic parameter grouped by measures of bone degradation (bioerosion, birefringence, and persistence of the periosteal surface) and visual diagenetic features (staining, inclusions and infiltrations).

5.1 NOTE ON THE DISPLAY OF STATISTICAL RESULTS

The regression models run in SPSS produced extensive outputs that detailed results pertaining to the influence of explanatory variables, the predictive power of the regression models and the appropriateness of ordinal regression. The objectives of the current study related to the influence of explanatory variables on dependent measures of diagenetic change. There was no intention to build accurate predictive models of diagenetic parameters. The imprecision of both dependent and explanatory variables used in the current study meant that it was unlikely that useful predictive models would be generated from the data that had been collected.

It was expected that the Test of Parallel Lines generated for the ordinal regression models would often reject the null hypothesis of proportional odds. This test is conservative in its rejection of the null hypothesis, particularly when incorporating large numbers of independent variables. The proportional odds assumption is most applicable to the appropriateness of ordinal regression equations as predictive models. The use of ordinal regression as an exploratory device meant that the assumption of proportional odds was not considered to be imperative to the use of ordinal regression models to identify influential explanatory variables. The role of the proportional odds assumption in the calculation of the parameter estimates meant that some of these values may have been slightly distorted in cases where the Test of Parallel Lines had failed. However, such an outcome would not have affected the identification of significant influencers of diagenetic parameters. Tests of Parallel Lines, as well as those figures that related to the predictive power of the ordinal and binary regression models, are available within Appendix 1. Only those results that were relevant to the influence of

explanatory variables (Parameter Estimate/B, Wald X^2, p-value) were included within the main text.

All ordinal and binary logistic regression SPSS outputs were included within Appendix 1. Several regression models were produced for all variables. Summary tables of these models were only included within this results chapter if they provided salient information regarding the factors that variably affected particular diagenetic parameters. P-values within tables are highlighted to reflect their significance. P-values less than 0.05 that indicated that an explanatory variable may have had an influence on a diagenetic parameter are highlighted in bold. Those values that were significant when the Holm-Bonferroni method was applied are marked out by a * symbol. Nagelkerke Pseudo R-Squared values were provided in some cases to highlight the proportion of variation within a dependent diagenetic parameter that was described by the significant explanatory variables and provide some gauge of the predictive power of the explanatory variables. Paired regressions that were performed to check the independence of more than two significant explanatory variables were not included in this chapter for the sake of brevity, but are available within Appendix 1.

5.2 Measures of Bone Degradation

Histological destruction of most bone samples (87%) used in this study had occurred as a result of bioerosion. Almost all (99%) of bioeroded samples demonstrated tunnelling that was morphologically consistent with Hackett's (1981: 250) non-Wedl MFD. Therefore, most measures of histological destruction, particularly Whole OHI score could be taken to represent measures of bacterial bioerosion. Fungal Wedl tunnelling was observed in 18% of samples, but in most cases this type of tunnelling had not destroyed enough of the bone microstructure to have affected Whole OHI score.

5.2.1 Comparisons of Measures of Bone Degradation

The status of Whole OHI score as a graduated ordinal gauge of histological destruction meant that this parameter represented the primary measure of bacterial bioerosion. Whole OHI score was tested against other measures of microstructural degradation to ensure that all variables

measured the same effect and confirm that Whole OHI score could be confidently used as a proxy for overall levels of histological destruction. Deviation of a measure of bone degradation from Whole OHI indicated that that the parameter reflected a different type of degradation and would have to be investigated separately.

5.2.1.1 Zonal OHI Score

Separate zonal OHI scores were produced for each third of a transverse thin section, running from the external to the internal surface (periosteal, internal, endosteal) The distribution of each zonal OHI score across all of samples were tested against Whole OHI score. Significant discrepancies between zonal and Whole OHI scores would suggest that the deviating zonal score corresponded to a discrete pathway of decay and that this variable would have to be investigated separately.

Zone	No. of samples	Spearman's Rho	Significance (p-value)
Periosteal	297	0.791	**0.000***
Internal	297	0.919	**0.000***
Endosteal	297	0.862	**0.000***

Table 5.1: Table of correlations between Zonal OHI scores and Whole OHI scores for the entire study sample.

There were significant positive correlations between all three Zonal OHI scores and Whole OHI (Table 5.1). All three zonal scores were likely to vary in similar ways to Whole OHI. The larger correlation coefficient attributed to the internal zone suggested that this section provides the best gauge of overall bacterial attack. Comparison of the distributions of Zonal OHI scores can be used to examine how bacterial bioerosion progressed within most bone samples. Higher numbers of endosteal zones were scored the lowest OHI scores compared to internal and periosteal areas (Figure 5.1). Periosteal OHI results were elevated and more widely distributed amongst the lower scores. Internal OHI scores were somewhere in the middle of those obtained from the periosteal and endosteal zones.

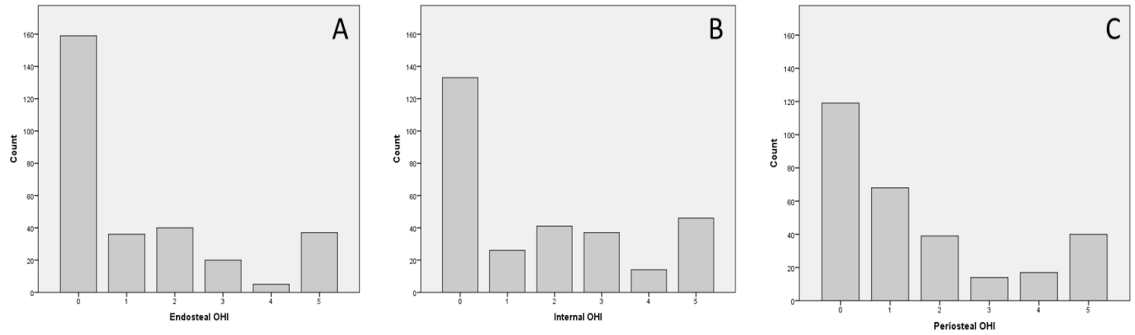

Figure 5.1: Distributions of Whole OHI scores amongst different zones of thin sections from across the entire study sample Distributions of scores for endosteal and internal zones were very similar. Periosteal surfaces tended to demonstrate comparatively elevated OHI scores reflecting the common perseverance of the periosteal surface (A=endosteal, B=internal, C=periosteal).

5.2.1.2 Presence of Bacterial Attack

There was a significant association between Whole OHI scores and the presence of bacterial attack (n=301, Mann-Whitney U=47.000, p=0.000). All but one of the samples that were free from bacterial bioerosion had been allocated the highest Whole OHI score of five (Figure 5.2). All bones that had been bioeroded demonstrated variable Whole OHI scores. The result emphasised that non-Wedl MFD were responsible for almost all histological destruction and variation in Whole OHI score. The presence of bacterial bioerosion was still considered separately from Whole OHI score in order to determine the factors that influenced the occurrence of non-Wedl MFD rather than just the severity of attack.

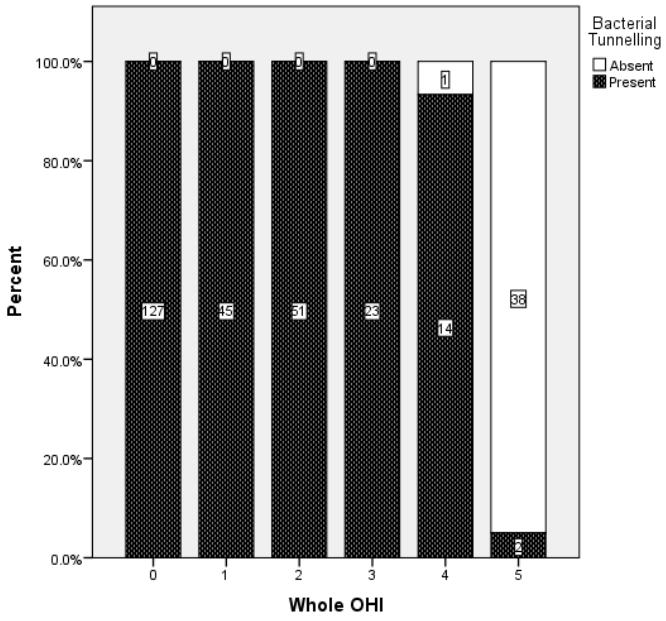

Figure 5.2: Proportional bar chart demonstrating the distribution of bones affected by bacterial bioerosion amongst remains that had been allocated variable Whole OHI scores. Numbers on the bars represent counts of cases.

5.2.1.3 Birefringence

There was a significant positive correlation between Whole OHI and Birefringence Index (n=301, Spearman's rho=0.411, p=0.000). The majority of variation in collagen birefringence was explained by collagen loss due to bacterial bioerosion. Bones that demonstrated high levels of histological preservation demonstrated high Birefringence Index scores (Figure 5.3). Collagen birefringence was likely to vary with the same factors as Whole OHI, and so there was no need to test Birefringence Index against any further variables.

A limited number of bone samples demonstrated reduced or absent birefringence despite remaining mostly free from bioerosion. Five outliers (2% of the whole sample) demonstrated a complete loss of birefringence despite attaining the highest Whole OHI scores of five. Two of these bones originated from the Roman Bantycock cemetery, whilst the other three consisted of isolated bones from the Carver Street, Royal Mint and Danebury sites. The low number of samples and their varied provenance meant that statistical investigation of possible causes of this non-biological collagen loss was unlikely to produce useful results. The exact circumstances that may explain the loss of collagen in each sample are discussed in the next chapter.

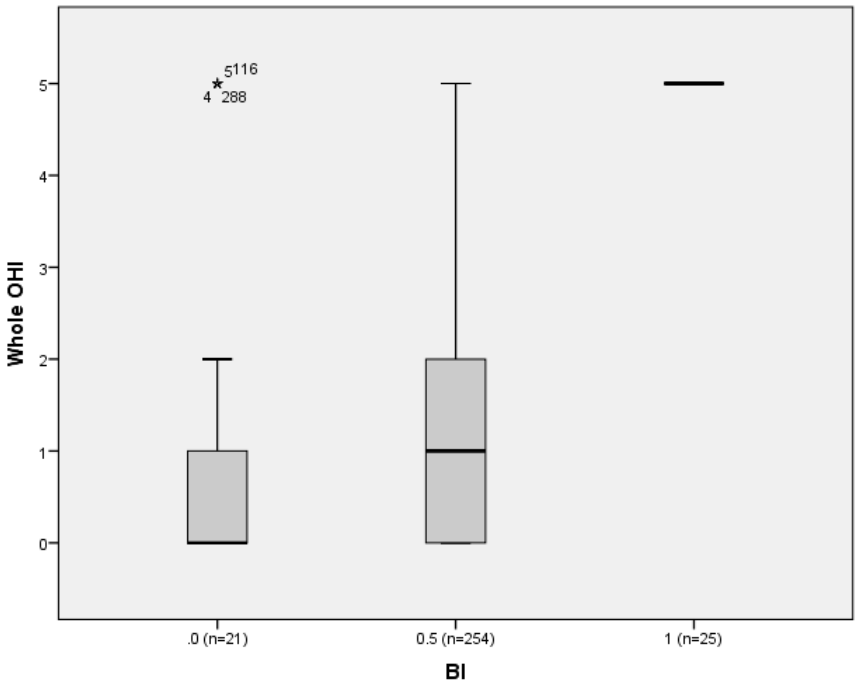

Figure 5.3: Box-and-whisker plot of Birefringence Index (BI) against Whole OHI for the whole study sample.

5.2.1.4 Wedl Tunnelling

Wedl tunnelling was recorded on a presence/absence basis. A Pearson's X^2 test of the relationship between Wedl tunnelling and Whole OHI score produced a p-value that was less than 0.05 (n=301, Fisher's Exact Test=14.930, p=0.008). When applying the Holm-Bonferroni method of correcting for multiplicity indicated that this result could not be accepted as significant (Appendix 2). Thus it was concluded that there was no relationship between Whole OHI score and Wedl Tunnelling (Figure 5.4).

Wedl tunnelling most often appeared within bone samples that also included non-Wedl MFD. The occurrence of Wedl tunnelling was lowest within the Whole OHI category that would have included bones that were free from bacterial attack. Wedl tunnelling was considered separately to the other measures of bone degradation in order to determine the factors had influenced its occurrence and explore how this parameter may be used in reconstructions of taphonomic events.

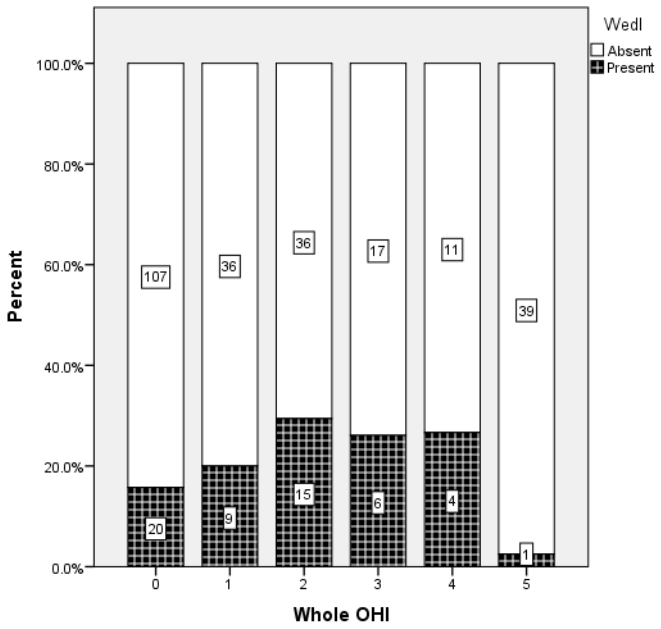

Figure 5.4: Proportional bar chart demonstrating the proportions of bone allocated each Whole OHI score that demonstrated Wedl tunnelling. Numbers on bars represent counts of cases.

5.2.1.5 Persistence of the Periosteal Surface

A Pearson's X^2 analysis of the relationship between Whole OHI score and persistence of the periosteal surface produced a p-value less than 0.05 (n=301, Fisher's Exact Test=11.252, p=0.034). However, the Holm-Bonferroni method determined that this result was not

significant (Appendix 2). There was no direct relationship between the extent of bacterial bioerosion and the loss of the periosteal surface (Figure 5.5). The persistence of the periosteal surface was tested separately in order to determine what factors affected its appearance and suggest how this parameter might be used in the inference of taphonomic processes.

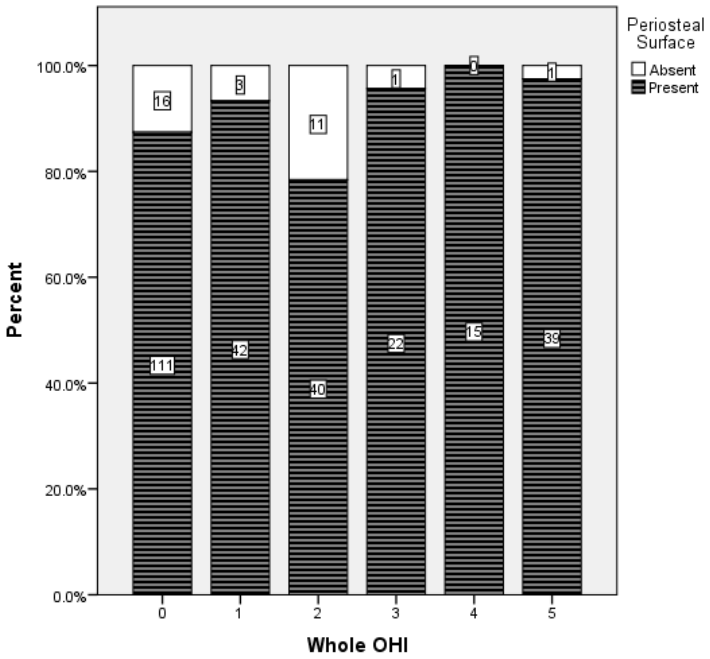

Figure 5.5: Proportional bar chart demonstrating the proportion of samples that had lost their periosteal surfaces within each Whole OHI score category. Numbers on bars represent counts of cases.

5.2.2 Variation in Whole OHI Score

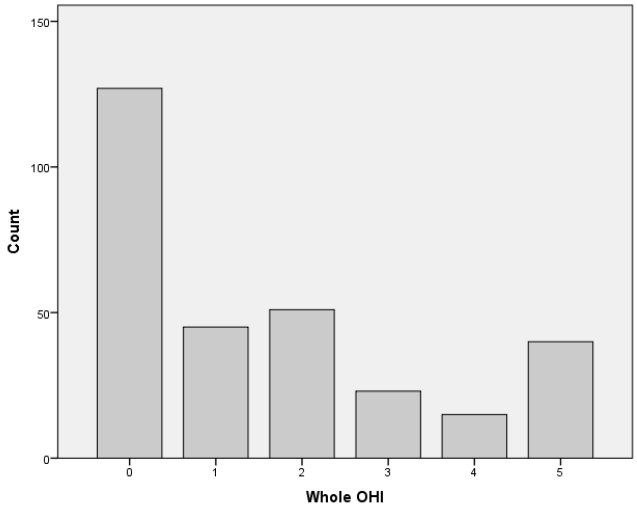

Figure 5.6: Histogram of the distribution of Whole OHI scores across the entire study sample.

The highest proportion of all samples (42%) demonstrated Whole OHI scores of zero (Figure 5.6). Seventy-four per cent of samples were scored one of the three lowest Whole OHI scores. When the mirrored Whole OHI distribution from all remains was compared against an idealised normal curve, there were clear deviations (Figure 5.7). There was an overrepresentation of Whole OHI scores of zero and, to a lesser extent, five within the observed distribution. There were also slight overrepresentations of scores of two and underrepresentation of three and four. The mirrored distribution of Whole OHI scores was significantly different from a normal model (n=475, Kolmogorov-Smirnov Z=2.914, p=0.000). This result suggested that there were significant levels of variation within Whole OHI score across the entire study sample. The multiple peaks indicated that several factors were likely to have influenced this parameter. The distribution of Whole OHI scores was tested against recorded variables within an ordinal regression model.

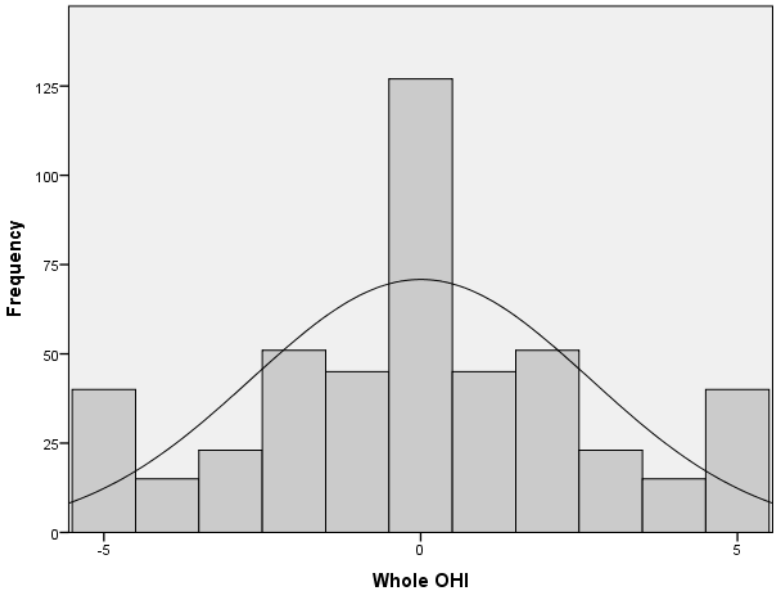

Figure 5.7: Histogram of the 'mirrored' distribution of Whole OHI scores across the entire study sample with a superimposed idealised normal curve. The mirrored distribution of Whole OHI scores does not conform to a normal model, particularly because of the number of bone samples allocated scores of zero and five.

Both ordinal and logistic regression do not work well when explanatory variables are highly correlated with one another, therefore choices had to be made over which similar variables (such as Phase and Specific Phase) were to be included. Phase was chosen over Specific Phase as the Later Prehistoric/Historical dichotomy was directly salient to the hypotheses set out in the Methodology chapter. Specific Phase was only variable within the Later Prehistoric subset. The variables that were left out would be tested at a later stage using non-parametric omnibus tests mediated by the Holm-Bonferroni method.

The majority (97%) of samples included in this study were taken from the femur whilst the remaining samples were taken from one of a variety of non-femoral long bones. It was important to establish whether sampling from variable skeletal elements affected levels of bacterial bioerosion. Initial tests suggested that non-femoral samples sizes were too variable and/or low to be tested using ordinal regression. Similarly, variable site sample sizes meant that specific site also had to be excluded from the ordinal regression. The potential influences of site-specific factors and skeletal element would be tested using non-parametric omnibus tests. Overall conclusions regarding their influence would have to be determined through comparison with results from the supplementary and specific site assemblages.

Variable	Outcome	Number of Samples	Estimate	Wald	Significance (p-value)
Anoxia	Absent	261	-2.064	31.574	**0.000***
	Present	40	0	-	-
Phase	Later Prehistoric	93	1.543	11.962	**0.001**
	Historical	208	0	-	-
Soil Type	Clay	159	-1.126	0.871	0.351
	Gravel	65	-0.916	0.552	0.457
	Sand	24	-0.034	0.001	0.977
	Silt	35	-1.562	2.040	0.153
	Open	18	0	-	-
Cave	Non-Cave	279	.477	0.199	0.656
	Cave	22	0	-	-
Black Death	Non Black Death	276	-1.456	9.077	**0.003**
	Black Death	25	0	-	-
State	Articulated	238	0.413	0.790	0.374
	Disarticulated	63	0	-	-
Charnel	Non-Charnel	213	-0.78	0.040	0.841
	Charnel	88	0	-	-
Age Range	Neonate	31	2.183	24.399	**0.000***
	Child	23	-1.020	4.110	0.043
	Juvenile	39	-0.186	0.292	0.589
	Adult	208	0	-	-

Table 5.2: Summary table of the Parameter Estimate from the second ordinal regression model of Whole OHI scores.

The first ordinal regression model of Whole OHI suggested that Anoxic Environment, Phase and Black Death deposits had influenced Whole OHI score (Appendix 1, page 569). The regression model only included those cells where there were values for all explanatory variables. A limited number of individuals had been assigned a biological sex. Therefore, any regression model that included the Sex variable would not have included all cases. The first

ordinal regression model established that Sex had no influence on Whole OHI score. The model was run again without Sex as an explanatory variable in order to produce an outcome that included the whole study sample. This sequential run of regression models with and without the Sex variable had to be repeated for each diagenetic parameter.

Anoxia, Phase and Black Death still influenced Whole OHI in the second ordinal regression model (Table 5.2; Appendix 1, page 571). Age Range also had an influence, although only the neonatal age category significantly affected Whole OHI Score. All of the non-significant explanatory variables were removed from the model in order to determine the nature of the influence of the significant variables. All variables maintained a significant influence on Whole OHI score within this third ordinal regression, which suggested that they had all independently influenced Whole OHI score (Table 5.3; Appendix 1, page 573). The Nagelkerke Pseudo R-Squared value for this ordinal regression suggested that these variables accounted for 21.9% of variation in Whole OHI score. The p-value of the parameter estimate associated with the Child Age Category dropped below 0.05. However the Holm-Bonferroni correction indicated that this result could not be accepted as significant at (Appendix 2).

Variable	Outcome	Number of Samples	Estimate	Wald	Significance (p-value)
Anoxia	Absent	261	-1.924	32.406	**0.000***
	Present	40	0	-	-
Phase	Later Prehistoric	93	1.101	18.413	**0.000***
	Historical	208	0	-	-
Black Death	Non Black Death	276	-1.431	12.484	**0.000***
	Black Death	25	0	-	-
Age Range	Neonate	31	2.028	29.032	**0.000***
	Child	23	-1.082	4.884	**0.027**
	Juvenile	39	-0.229	0.468	0.494
	Adult	208	0	-	-

Table 5.3: Summary table of the Parameter Estimates from the third ordinal regression model of Whole OHI scores.

Each of the significant explanatory variables was paired against the others within separate ordinal regression models to further test whether each represented an independent source of variation in Whole OHI score (Appendix 1, page 586). Age Range, Phase and Anoxic environment all maintained significant influences on Whole OHI score when paired with all other significant variables. However, the p-value of the Black Death variable became non-significant (p= 0.088) when it was placed in a regression model with Age Range. The

significance of the Black Death variable within the third regression model and when it was placed in regression models with the two other significant variables meant that its influence on Whole OHI was still considered. However, it was possible the influence of this variable on Whole OHI score may not have been entirely independent of Age Category.

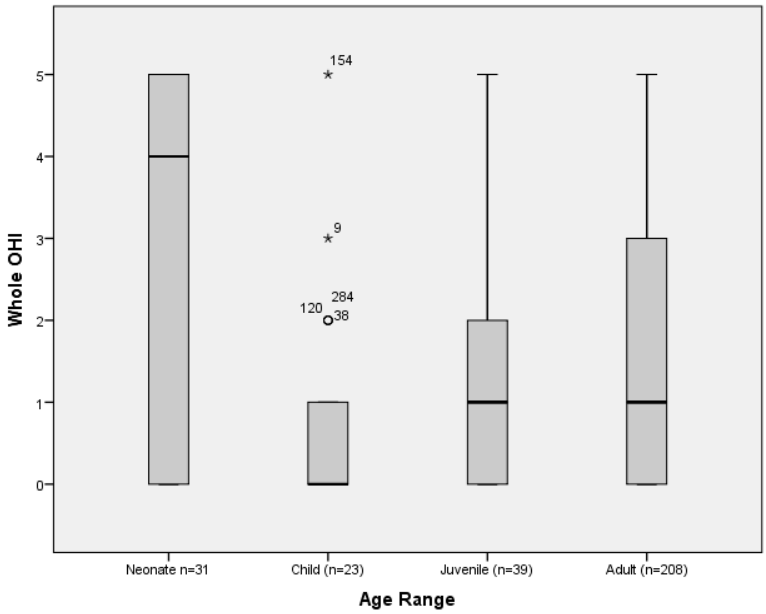

Figure 5.8: Box-and-whisker plot of distributions of Whole OHI scores amongst all bones grouped by age-at-death.

Age Range had the largest effect on Whole OHI score as defined by the parameter estimate. Neonatal bones were significantly more likely to demonstrate higher Whole OHI scores than bones from all other age categories. Neonatal remains explained the all variation in Whole OHI score by age-at-death (Figure 5.8). The variable that had the next largest influence on Whole OHI score was the presence of an anoxic environment. The parameter estimates suggested that remains from anoxic environments were more likely to demonstrate higher levels of histological preservation than bones from aerobic contexts (Figure 5.9). When the neonatal remains were removed, the distribution of Whole OHI scores within the anoxic-deposited samples, as defined by the interquartile range, was elevated and wider compared to bones from aerobic environments.

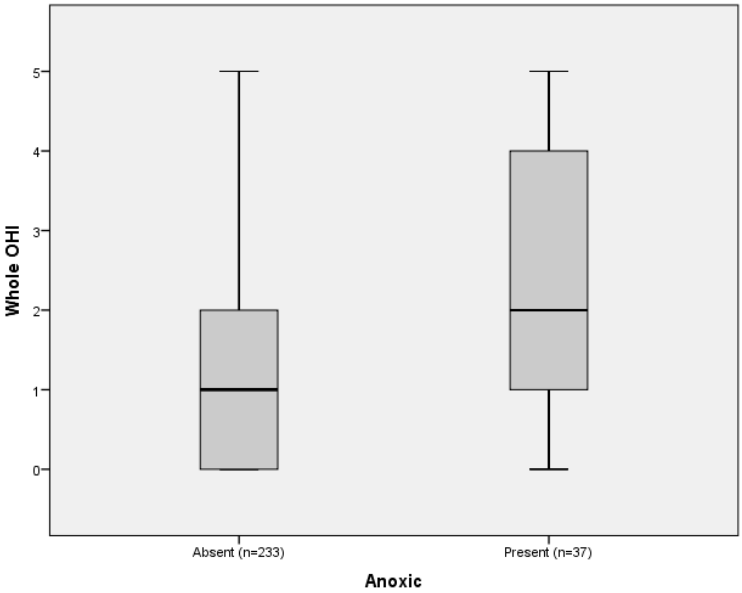

Figure 5.9 Box-and-whisker plot of the distributions of Whole OHI scores amongst remains variably retrieved from an anoxic environment (Neonatal remains were excluded).

The next significant variable within the ordinal regression equation was whether or not a sample originated from a Black Death cemetery. Bones from the Black Death graves were more likely to demonstrate higher Whole OHI scores than those from non-Black Death contexts (Figure 5.10). When the neonatal and anoxic-deposited remains were disregarded, the Black Death remains demonstrated a comparatively elevated median Whole OHI score compared to the non-Black Death samples.

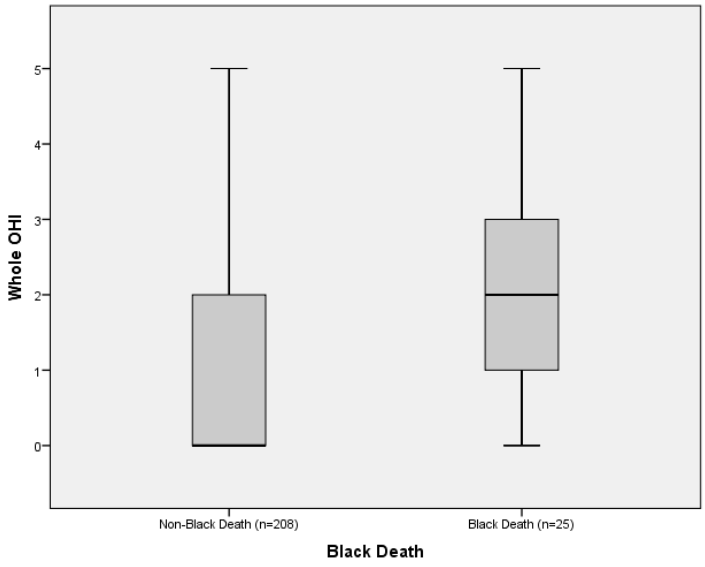

Figure 5.10: Box-and-whisker plot of the distribution of Whole OHI scores amongst remains variably retrieved from a Black Death cemetery (Neonatal and Black Death remains were excluded).

The variable that had the next most powerful effect on Whole OHI score was whether a bone originated from a Historical or Later Prehistoric context. The parameter estimate suggested that bones from Later Prehistoric contexts were more likely to demonstrate high Whole OHI scores. This pattern was supported by the higher median Whole OHI value of the Later Prehistoric assemblage, minus the neonatal, anoxic-deposited and Black Death samples (Figure 5.11). The interquartile range of the Later Prehistoric assemblage was wider than that of the Historical sample, which suggested that histological preservation amongst the Later Prehistoric samples was more variable. Whole OHI scores of the Historical samples were centred on a median score of zero and demonstrated a restricted interquartile range, which suggested that histological preservation of this sample set was invariably low.

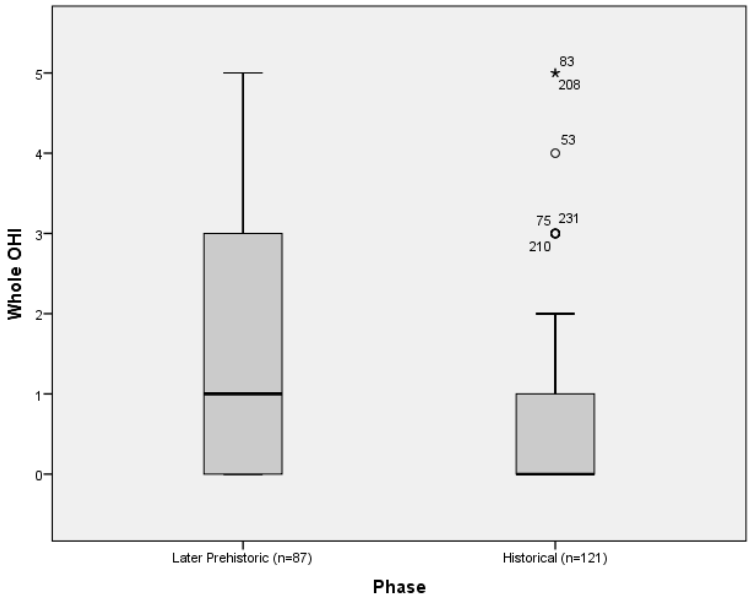

Figure 5.11: Box-and-whisker plot of the distribution of Whole OHI scores amongst remains from Historical and Later Prehistoric contexts (Neonatal, anoxic-deposited and Black Death remains were excluded).

5.2.2.1 Variation in Whole OHI Score amongst the Historical Assemblage

It was predicted within the hypotheses set out in the Background chapter (page 98) that if bacterial bioerosion of bone related to funerary treatment in a way that could be predicted by models of decomposition, the distribution of Whole OHI scores amongst the Historical remains would be half-normal. The ordinal regression had indicated that neonatal remains, anoxic environments and bones from Black Death cemeteries demonstrated elevated levels of histological preservation. The potential distorting influence of these factors had been

predicted in previous chapters, based on the results of previous studies as well as information from specific archaeological sites. The distribution of Whole OHI scores amongst post-neonatal Historical remains that had not been retrieved from an anoxic or Black Death context should have represented the expected distribution from archaeological remains that had been buried immediately after death and exposed to consistently high levels of uninterrupted putrefaction. The distribution of Whole OHI scores amongst this Historical baseline assemblage resembled a smooth half normal model (Figure 5.12).

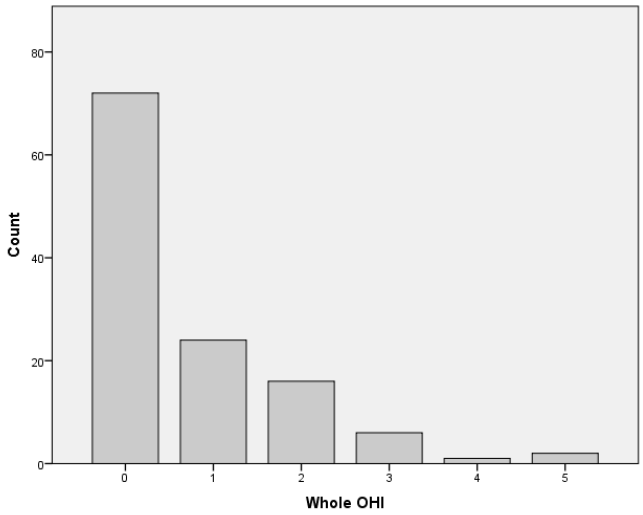

Figure 5.12: Histogram of the distribution of Whole OHI scores amongst the Historical remains minus anoxic-deposited, neonatal and Black Death remains, representing the Historical baseline distribution of Whole OHI scores relating to primary burial.

However, there was a statistically significant difference between the mirrored version of the Historical baseline distribution and an idealised normalised curve (n=170, Kolmogorov-Smirnov Z=2.761, p=0.000). The mirrored Historical baseline Whole OHI distribution differed from a normal curve by the number of remains that had been allocated low Whole OHI scores, particularly zero (Figure 5.13). The Historical baseline distribution was significantly leptokurtic compared to a normal model (Pearson's measure of kurtosis=1.544, Standard Error of Kurtosis = 0.370, Ratio=4.17). A distribution can be considered to be significantly leptokurtic when the ratio between the measure and standard error of kurtosis is positive and greater than two. It was the leptokurtic shape of the Historical baseline distribution that constituted its main deviation from a normal model.

Leptokurtic distributions are characterised by high thin central peaks and short, heavy tails. This distribution is produced when data points are highly concentrated around the mean and is symptomatic of low variance. The result from the mirrored distribution indicated that the

Historical baseline distribution of Whole OHI scores was significantly less variable around scores of zero than a half-normal curve.

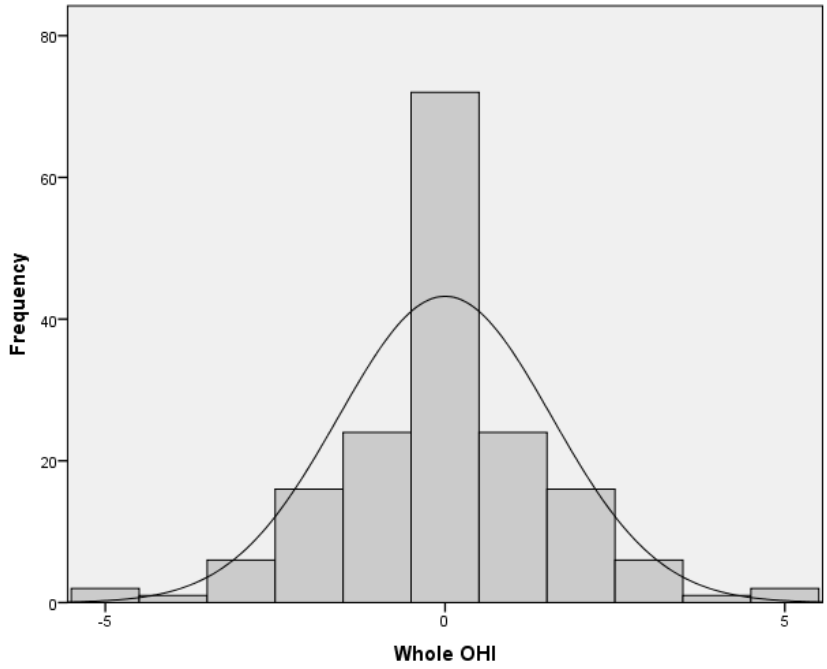

Figure 5.13: Histogram of the 'mirrored' distribution of Whole OHI scores amongst the Historical baseline assemblage with a superimposed idealised normal distribution. The Whole OHI distribution is significantly leptokurtic.

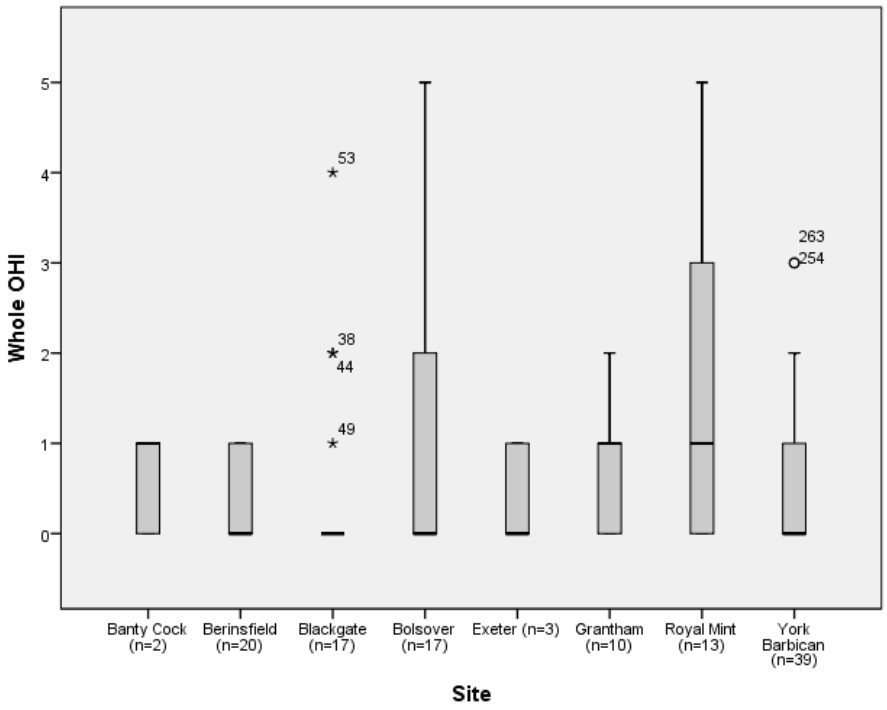

Figure 5.14: Box-and-whisker plot of Whole OHI scores within collections of bones from discrete Historical sites (neonatal, anoxic-deposited and Black Death samples were excluded).

The other test of the first and second hypotheses regarding the relationship between bacterial bioerosion and funerary treatment set out in the Background chapter (page 98) was the expectation that bacterial bone bioerosion should be consistently extensive within different Historical site assemblages. When the neonatal, anoxic deposited and Black Death bones were excluded, there were no significant differences in distributions of Whole OHI scores between separate Historical assemblages (n=121 Kruskal-Wallis X^2=11.402, p=0.122). Bone samples from all Historical sites demonstrated similar high levels of bacterial attack (Figure 5.14).

5.2.2.2 Variation in Whole OHI score amongst the Later Prehistoric Assemblage

It was pertinent to compare the mirrored distribution of the Later Prehistoric samples against an idealised normal model to investigate how Whole OHI scores within this assemblage differed from the distribution amongst the Historical bone samples. This comparison would help to characterise Later Prehistoric variation in Whole OHI score. The frequency distribution of Whole OHI scores amongst the Later Prehistoric remains without the anoxic-deposited and neonatal samples retained a central tendency towards low Whole OHI scores (Figure 5.15). However the distribution demonstrated two secondary peaks at scores of two and five. These two peaks represented the point of deviation between the Whole OHI scores of the Historical and Later Prehistoric assemblages.

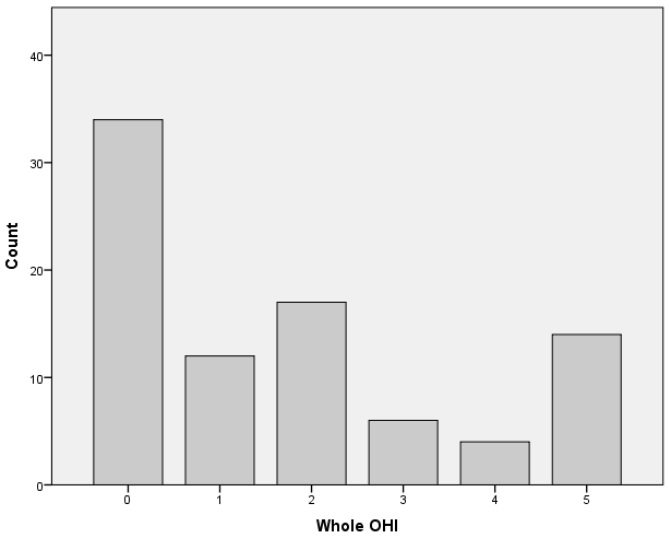

Figure 5.15: Histogram of the frequency distribution of Whole OHI scores amongst the Later Prehistoric assemblage (neonatal and anoxic-deposited remains were excluded).

There was a significant difference between the mirrored Later Prehistoric distribution of Whole OHI scores, excluding the neonatal and anoxic-deposited remains, and an idealised normal plot (n=140, Kolmogorov-Smirnov Z=1.437, p=0.032). A high proportion of Later Prehistoric remains were allocated Whole OHI scores of zero (Figure 5.16). However, the Whole OHI distribution was platykurtic, although this result was not significant (Pearson's test of kurtosis=-0.518, standard error= 0.407, Ratio=1.27). Platykurtic distributions are characterised by lower central peaks and long thin tails. These distributions reflect an excess of variation around the mean. This result emphasised the different levels of variability within the Later Prehistoric and Historical baseline distributions of Whole OHI scores.

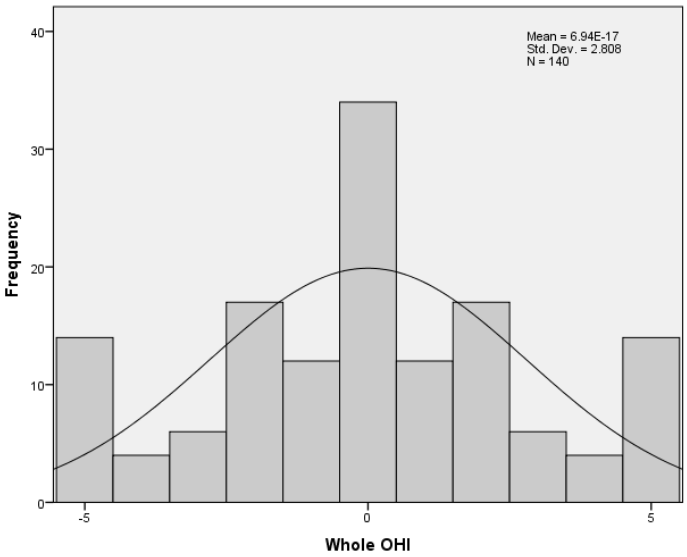

Figure 5.16: Histogram of the distribution of Whole OHI scores across the Later Prehistoric assemblage with a superimposed idealised normal distribution (neonatal and anoxic-deposited remains were removed).

The deviation of the Later Prehistoric Whole OHI distribution was not explained by its platykurtic shape. This distribution deviated from a normal model by the overrepresentation of scores of zero, two and five and an underrepresentation of scores of three, four and one. One or more factors intrinsic to the Later Prehistoric remains must have produced the three peaks within the data. The Specific Phase variable, which divided Later Prehistoric remains by Neolithic, Bronze Age and Iron Age, was not included in the original ordinal regression model. There was no significant difference in Whole OHI scores between Later Prehistoric remains from different Specific Phases (Neolithic=35, Bronze Age=28, Iron Age=24, Kruskal-Wallis X^2=2.592, p=0.274).

Site-specific Later Prehistoric variation in bacterial bioerosion might account for some of the unexplained variation in Whole OHI score. When the neonatal and anoxic-deposited samples

were excluded a Kruskal -Wallis analysis of the difference in Whole OHI scores between remains from discrete Later Prehistoric sites, produced a p-value of less than 0.05 (n=87, Kruskal-Wallis X^2=24.576, p=0.026). However the Holm-Bonferroni method determined that this result was not significant (Appendix 2). Whole OHI scores amongst remains from different Later Prehistoric sites were consistently variable (Figure 5.17).

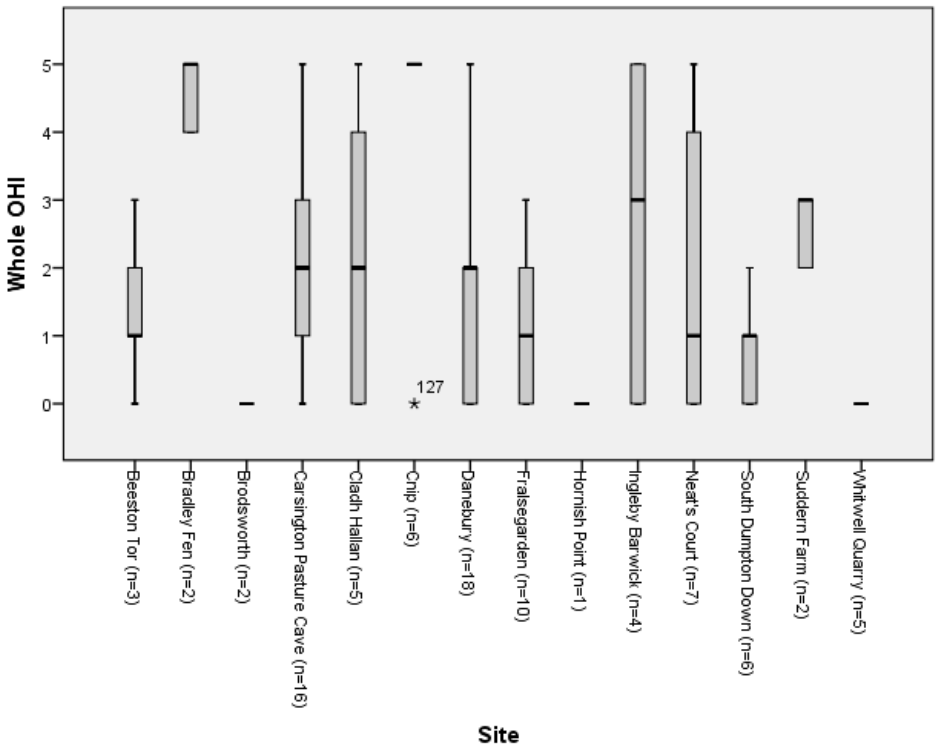

Figure 5.17: Box-and-whisker plot of distributions of Whole OHI scores within groups of remains from discrete Later Prehistoric sites (neonatal and anoxic-deposited remains were excluded).

5.2.2.3 Effect of Skeletal Element on Whole OHI Score

Attempts to determine the extent to which skeletal element influenced bacterial bioerosion within the samples included in the current study were undermined by the low number of non-femoral samples. Some of the skeletal elements that were included only appeared once within the entire assemblage. A Kruskal-Wallis X^2 test of Whole OHI scores amongst different skeletal elements produced a p-value that was less than 0.05 (Femur=298, Fibula=1, Humerus=6, Metatarsal=1, Radius=1, Tibia=3, Kruskal-Wallis X^2=14.296, p=0.014). However, the Holm-Bonferroni method determined that this result was not significant (Appendix 2). It was unlikely that variation in bacterial bioerosion within the study sample was attributable to variation in skeletal element.

5.2.3 Variation in the Presence of Bacterial Attack

Variable	Outcome	Number of Samples	B	Wald	Significance (p-value)
Anoxia	Present/Absent	301	3.441	12.297	**0.000***
Phase	Later Prehistoric/Historical	301	-2.437	7.970	**0.005**
Soil Type	Overall	301	-	4.189	0.381
	Clay	*159*	*2.585*	*0.000*	*1.000*
	Gravel	*65*	*1.128*	*0.000*	*1.000*
	Sand	*24*	*1.167*	*0.000*	*1.000*
	Silt	*35*	*22.314*	*0.000*	*0.999*
	Open	*18*	*0*	-	-
Cave	Cave/Non-Cave	301	-2.722	0.000	1.000
Black Death	Non-Black Death/Black Death	301	0.686	0.431	0.512
State	Articulated/Disarticulated	301	0.867	1.083	0.298
Charnel	Non-Charnel/Charnel	301	-0.976	1.235	0.326
Age Range	Overall	301	-	24.150	**0.000***
	Neonate	31	*-4.193*	*23.320*	***0.000****
	Child	23	*0.310*	*0.066*	*0.797*
	Juvenile	39	*0.014*	*0.000*	*0.984*
	Adult	208	*0*	-	-

Table 5.4: Summary table of the Parameter Estimates for the second binary logistic regression of the presence of bacterial attack.

Non-Wedl MFD were present within 87% of the whole study sample. The factors that influenced the occurrence of bacterial bioerosion were modelled using binary logistic regression. The first model tested all possible explanatory variables against the presence of bacterial bioerosion (Appendix 1, page 582). Anoxic Environment and Phase had influenced the presence of bacterial bioerosion within this model. The first model established that Sex had not influenced bacterial bioerosion. Logistic regression was repeated without the Sex variable.

The second model indicated that Anoxic Environment, Phase and Age Range influenced the occurrence of bacterial bioerosion (Table 5.4; Appendix 1, page 584). Bacterial attack was only influenced by the neonatal category within Age Range. The model was run again with only the significant variables to determine the power and dependence of their influence. Most variables maintained significant levels of influence within this third model (Appendix 1, page 585). The p-value associated with Anoxia was low but non-significant when the Holm-Bonferroni method was applied (Appendix 2). This low p-value and the significance of Anoxia

within the second regression model meant that Anoxia was still considered as a potential factor that explained variation in the occurrence of bacterial attack. Neonatal Age remained the only factor within Age Category that enacted a statistically significant influence on the presence of bacterial bioerosion (Table 5.5). The Nagelkerke R-squared generated for this model suggested that these variables accounted for 28.5% of variation in the presence of bacterial bioerosion. All significant explanatory variables were paired with one another within further binary logistic regression models to explore their independence (Appendix 1, page 586). All variables maintained their significant influence when tested alongside one another, which indicated that they represented independent affecters of bacterial bioerosion.

Variable	Outcome	Number of Samples	B	Wald	Significance (p-value)
Anoxia	Present/Absent	301	1.915	11.144	**0.001**
Phase	Later Prehistoric/Historical	301	-1.933	14.462	**0.000***
Age Range	Overall	301	-	33.419	**0.000***
	Neonate	*31*	*-3.167*	*31.276*	***0.000****
	Child	*23*	*0.542*	*0.255*	*0.613*
	Juvenile	*39*	*-0.260*	*0.185*	*0.667*
	Adult	*208*	*0*	-	-

Table 5.5: Summary table of the Parameter Estimates for the third binary logistic regression of the presence of bacterial attack.

Age Range had the largest influence on the presence of bacterial bioerosion, as defined by the size of the parameter estimate. All variation was attributable to the neonatal samples. Neonatal bone samples were more likely to remain free from bacterial bioerosion than post-neonatal samples (Figure 5.18). This trend was likely to be responsible for the high levels of correspondence between neonatal status and Whole OHI score. The factor that had the next largest influence on the presence and absence of bacterial bioerosion was Phase. Later Prehistoric bones were significantly more likely to have remained free from bacterial bioerosion than their Historical counterparts (Figure 5.19). The final variable that had influenced the presence of bacterial bioerosion was Anoxic Environment. Bones from anoxic contexts were more likely to have remained free from bacterial bioerosion than those from aerobic environments. Only two Later Prehistoric samples had been recovered from anoxic environments. Both were free from bacterial attack. The majority of anoxic-deposited Historical remains had been bioeroded, but a significantly larger proportion of these bones

were free from bacterial bioerosion when compared to samples from aerobic contexts (Figure 5.20).

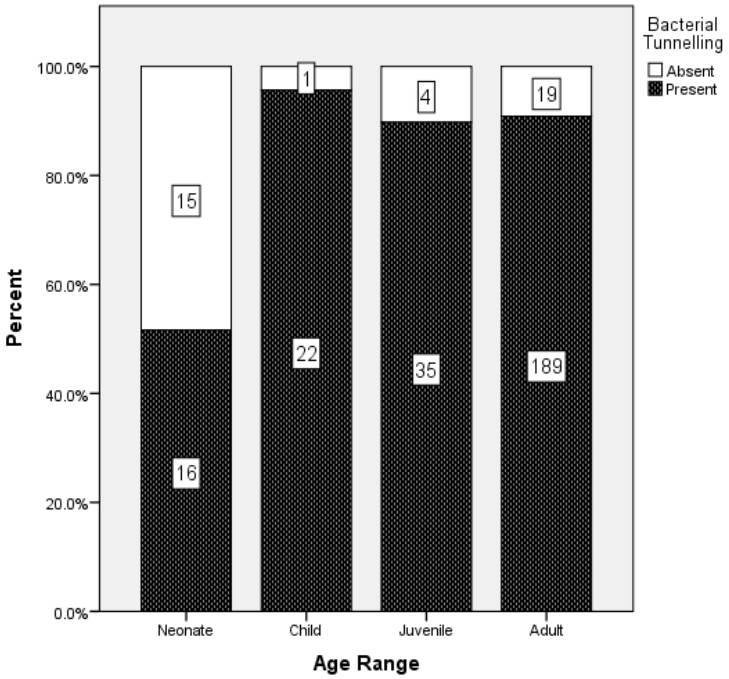

Figure 5.18: Proportional bar chart illustrating the presence of bacterial attack within remains allocated different age-at-death ranges.

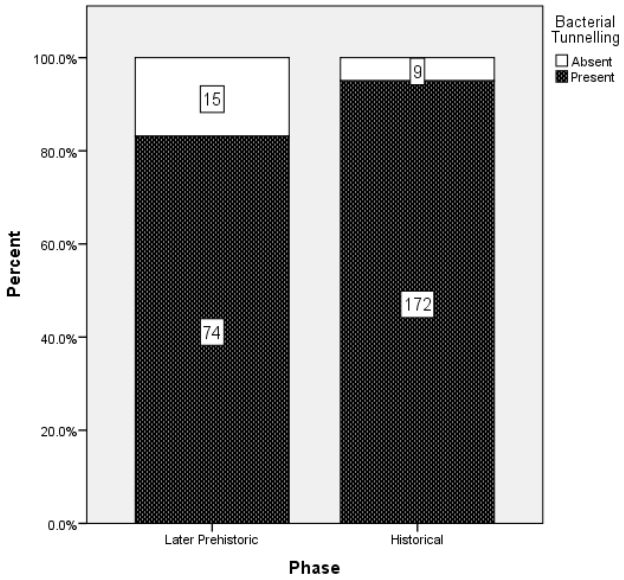

Figure 5.19: Proportional bar chart illustrating the presence of bacterial attack within the Later Prehistoric and Historical remains (neonatal bones were excluded). Numbers on bars represent counts of cases.

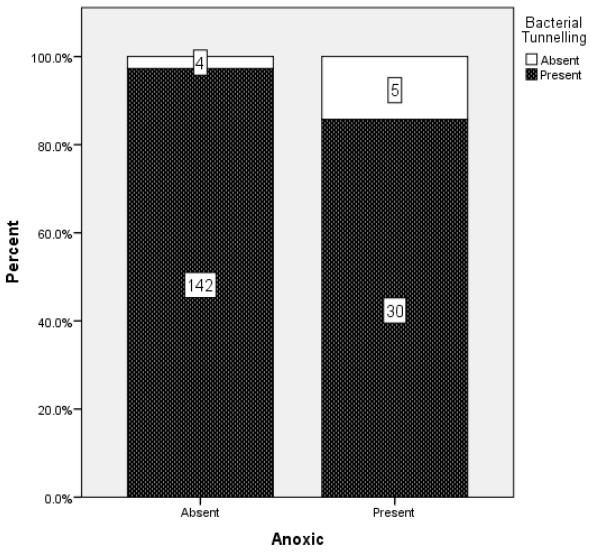

Figure 5.20: Proportional bar chart of the presence of bacterial attack within Historical remains (neonatal samples were excluded).Numbers on bars represent counts of cases.

Historical site-specific differences in the presence of bacterial bioerosion were examined to assess whether factors exclusive to particular sites may have inhibited bacterial bioerosion of bone. When the neonatal remains and the bones from the anoxic environments were removed, two of the eight remaining Historical sites included bones that demonstrated no internal bacterial tunnelling (Figure 5.21). There was no statistically significant difference in the occurrence of non-Wedl MFD amongst bones from discrete Historical sites (n=146, Fisher's Exact=7.119, p=0.431).

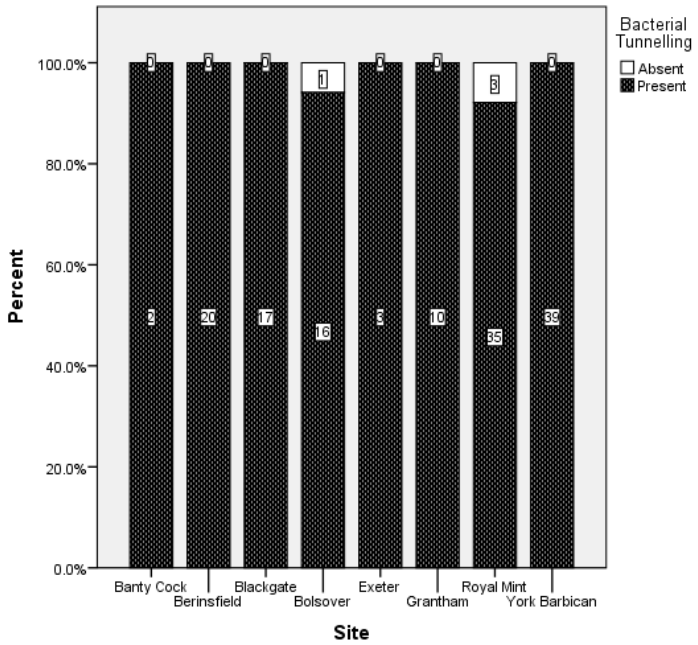

Figure 5.21: Proportional bar chart displaying the distributions of bioeroded bones amongst Historical site assemblages (neonatal and anoxic-deposited samples were excluded). Numbers on bars represent counts of cases.

The high numbers of post-neonatal Later Prehistoric remains that were free from bacterial bioerosion represented variation that required an explanation. Later Prehistoric Specific Phase had not been included within the logistic regression model. A Kruskal-Wallis X^2 analysis of the presence of bacterial bioerosion within bones from separate Specific Later Prehistoric Phases produced a p-value that was less than 0.05 (n=87, Kruskal-Wallis X^2=13.606, p=0.003). However, the Holm-Bonferroni method determined that this result was not significant (Appendix 2).

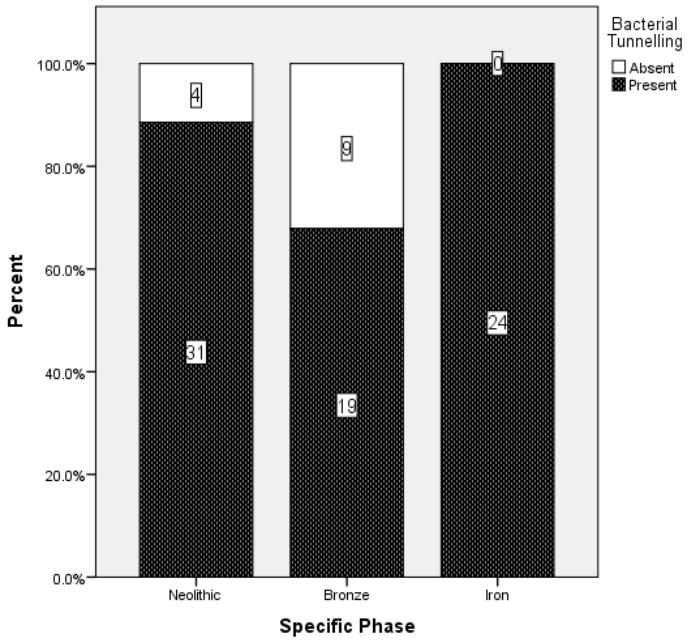

Figure 5.22: Proportional bar chart of the presence of bacterial attack within Later Prehistoric remains grouped by Specific Phase (neonatal and anoxic-deposited samples were excluded). Numbers on bars represent counts of cases.

This result was close to the significance threshold within the Holm-Bonferroni method. The Holm-Bonferroni method is conservative, which increases the risk of Type II error. Previous analyses had failed to identify the source of variation in patterns of bacterial bioerosion within Later Prehistoric remains. Specific Phase was cautiously considered as a potential explanatory variable for Later Prehistoric variation in the presence of bacterial attack. Large proportions of Bronze Age bones were free from microbial bioerosion (Figure 5.22). Distributions of unbioeroded remains within the Iron Age and Neolithic remains were similarly low. The Bronze Age remains explained the majority of the variation in the occurrence of bacterial attack by Specific Phase.

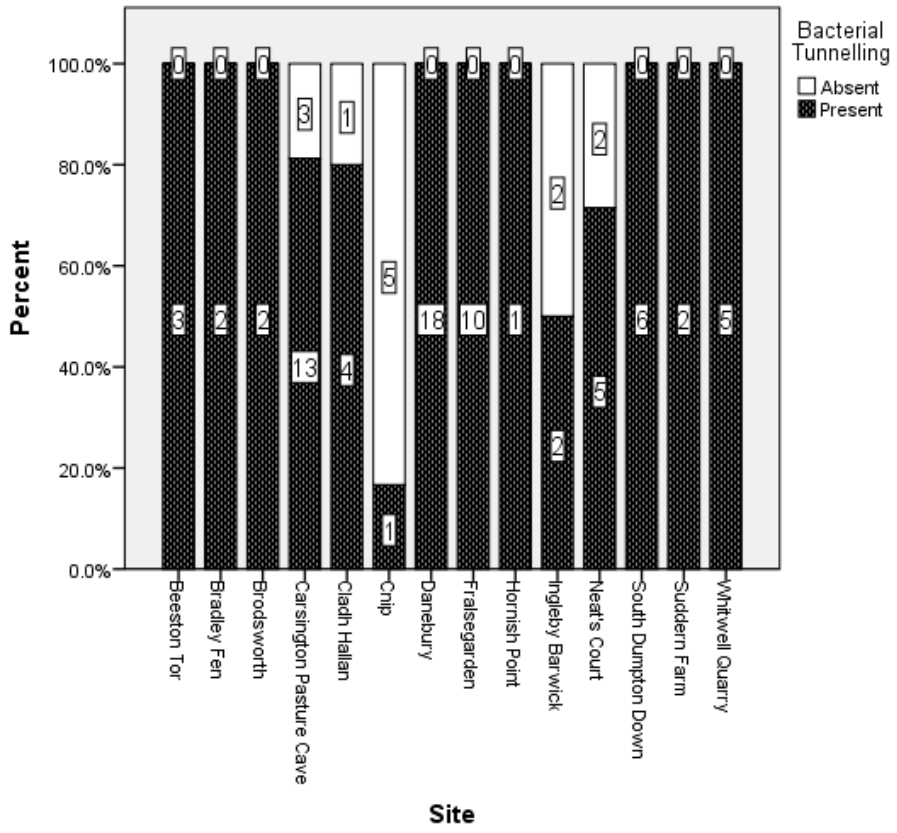

Figure 5.23: Proportional bar chart of the presence of bacterial attack within the Later Prehistoric remains grouped by site assemblage (neonatal and anoxic-deposited remains were excluded). Numbers on bars represent counts of cases.

The presence of bacterial bioerosion was examined between remains from separate Later Prehistoric site assemblages to assess how far site-specific factors may have inhibited bacterial bone bioerosion. When the neonatal and anoxic-deposited samples were removed, a Pearson's X^2 test of the differences in the presence of bacterial bioerosion between site assemblages produced a p-value that was less than 0.05 (n=87, Fisher's Exact=26.104, p=0.001). However, the Holm-Bonferroni method determined that this result could not be accepted as significant (Appendix 2). This result was close to the significance threshold of the Holm-Bonferroni method. Five of the remaining fourteen Later Prehistoric sites included remains that demonstrated no bacterial tunnelling (Figure 5.23). Four out of five of these sites included remains that dated to the Bronze Age.

5.2.4 The Nature of Bacterial Bioerosion amongst the Neonatal Samples

The absence of bacterial bioerosion from a large proportion of the neonatal samples may have been responsible for their significantly high Whole OHI scores. Whole OHI scores amongst those neonatal samples that had been bioeroded was similar to the distribution of scores amongst the Historical baseline assemblage (Figure 5.24). There was no statistically significant difference between these two distributions (n=286, Mann-Whitney U=1841.000, p=0.296) This result confirmed that the significantly high Whole OHI scores of the neonatal samples were not a result of generally lower levels of bacterial bioerosion, but solely due to an absence of this type of tunnelling from a significant proportion of neonatal samples.

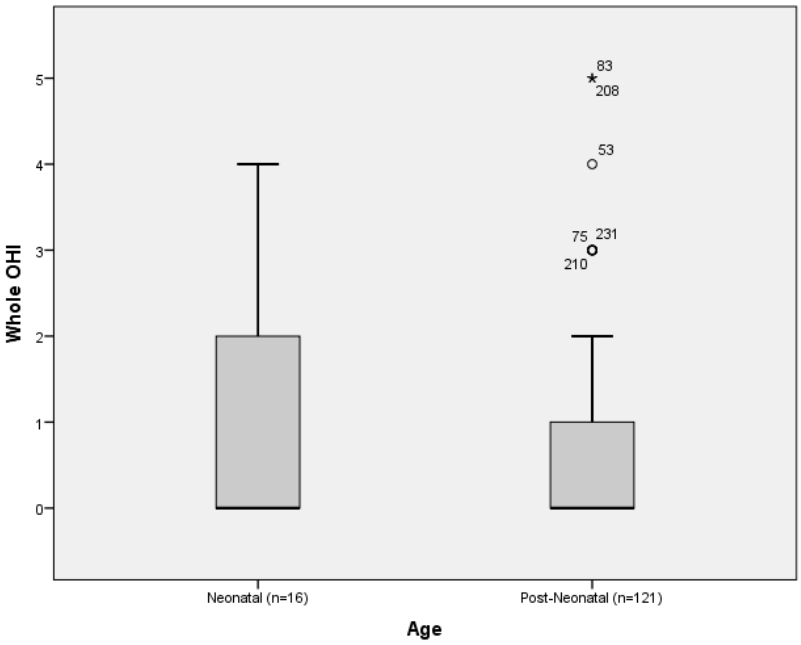

Figure 5.24: Box-and-whisker plot of the distribution of Whole OHI scores amongst the neonatal and post-neonatal remains (neonatal remains that were free from bacterial bioerosion were excluded).

5.2.5 Variation in the Presence of Wedl Tunnelling

Wedl tunnelling represented fungal bioerosion and was recorded on a presence/absence basis (Marchiafava *et al.* 1974). Eighteen-per-cent of all samples demonstrated Wedl tunnelling. The presence of Wedl MFD was tested against all recorded explanatory variables using binary logistic regression to determine the factors associated with its appearance and whether the presence of Wedl tunnelling could be used to infer anything useful about the taphonomic history of remains.

The first model indicated that only the presence of a sand environment significantly influenced the occurrence of Wedl tunnelling (Appendix 1, page 590). Confirmation that Sex was not influential meant that this variable could be discounted and the model was run again. In the second regression Soil Type no longer influenced Wedl tunnelling (Table 5.6; Appendix 1, page 591). Phase influenced the occurrence of fungal bioerosion within this model. Retrieval of remains from a Cave or Charnel Deposit was also influential within the second regression.

Variable	Outcomes	Number of Samples	B	Wald	Significance (p-value)
Anoxia	Present/Absent	301	0.041	0.007	0.935
Phase	Later Prehistoric/Historical	301	1.190	3.180	0.075
Soil Type	Overall	301	-	3.564	0.468
	Clay	*159*	*-0.234*	*.028*	*0.868*
	Gravel	*65*	*0.467*	*0.101*	*0.750*
	Sand	*24*	*-1.563*	*0.885*	*0.347*
	Silt	*35*	*-0.551*	*4.089*	*0.683*
	Open	*18*	*0*	-	-
Cave	Cave/Non-Cave	301	-2.482	4.089	**0.043**
Black Death	Non-Black Death/Black Death	301	0.933	1.201	0.273
State	Articulated/Disarticulated	301	0.840	1.290	0.256
Charnel	Non-Charnel/Charnel	301	-0.914	2.177	0.140
Age Range	Overall	301	-	2.365	0.500
	Neonate	*31*	*-1.310*	*2.320*	*0.128*
	Child	*23*	*0.018*	*0.001*	*0.977*
	Juvenile	*39*	*-0.048*	*0.010*	*0.921*
	Adult	*208*	*0*	-	-

Table 5.6: Summary table of the Parameter Estimates relating to the second binary logistic regression model of the presence of Wedl tunnelling.

The Logistic Regression model was repeated with these three variables (Appendix 1, page 593). The parameter estimates of this third model indicated that acquisition of remains from Charnel Deposits or Caves mostly influenced the occurrence of Wedl bioerosion (Table 5.7). Phase no longer influenced Wedl tunnelling. However, when the model was run once more with just the Cave and Charnel explanatory variables, Charnel no longer demonstrated an influence on the presence of Wedl tunnelling, whilst the influence of Cave Deposits became significant under the Holm-Bonferroni method (Table 5.8; Appendix 1, page 594; Appendix 2). The influence of the Cave variable on Wedl tunnelling remained statistically significant when modelled by itself (n=301, B= -2.318, Wald X^2=23.885, p=0.000) (Appendix 1, page 594). The Nagelkerke R-squared value indicated that this variable accounted for 12.7% of the variation in the presence

of Wedl tunnelling. The B value within the logistic regression suggested that bones from caves were more likely to demonstrate Wedl tunnels (Figure 5.25).

Variable	Outcomes	Number of Samples	B	Wald	Significance (p-value)
Phase	Later Prehistoric/Historical	301	0.501	1.253	0.263
Cave	Cave/Non-Cave	301	-2.256	16.743	**0.000***
Charnel	Non-Charnel/Charnel	301	-0.839	4.335	**0.037**

Table 5.7: Summary table of the Parameter Estimates from the third binary logistic regression model of the presence of Wedl tunnelling.

Variable	Outcomes	Number of Samples	B	Wald	Significance (p-value)
Cave	Cave/Non-Cave	301	-2.548	26.408	**0.000***
Charnel	Non-Charnel/Charnel	301	0.630	3.331	0.068

Table 5.8: Summary of the Parameter Estimates from the fourth binary logistic regression model of presence of Wedl tunnelling.

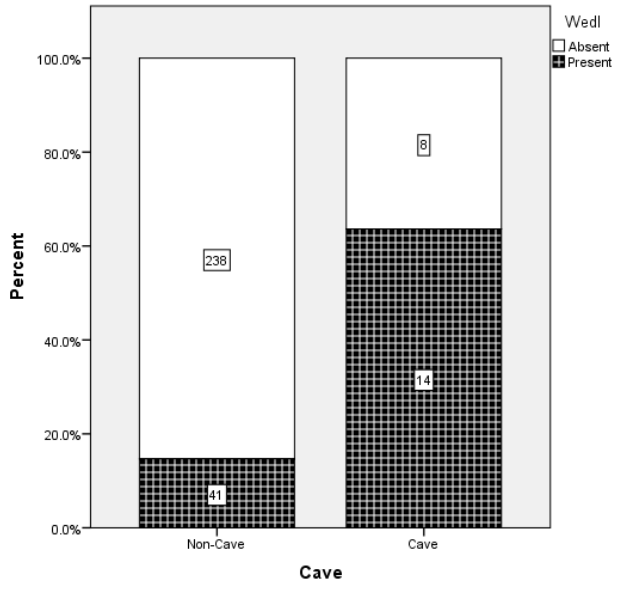

Figure 5.25: Proportional bar chart demonstrating the different rates of Wedl tunnelling amongst remains variably retrieved from caves. Numbers on bars represent counts of cases.

A substantial proportion of samples still demonstrated Wedl tunnelling when cave-deposited bones were excluded. The final variable that could be tested was the distribution of fungal tunnelling amongst different site assemblages. There was a significant difference in rates of Wedl tunnelling within separate site assemblages (n=191, Fisher's Exact=38.220. p=0.000).

Occurrences of Wedl tunnelling were particularly high within remains from the Later Prehistoric sites of Neat's Court, Brodsworth, Danebury and Suddern Farm, although sample sizes at Brodsworth and Suddern Farm were low (n=2 in both cases) (Figure 5.26). The only Historical assemblage that demonstrated relatively elevated occurrences of fungal tunnelling was the Royal Mint.

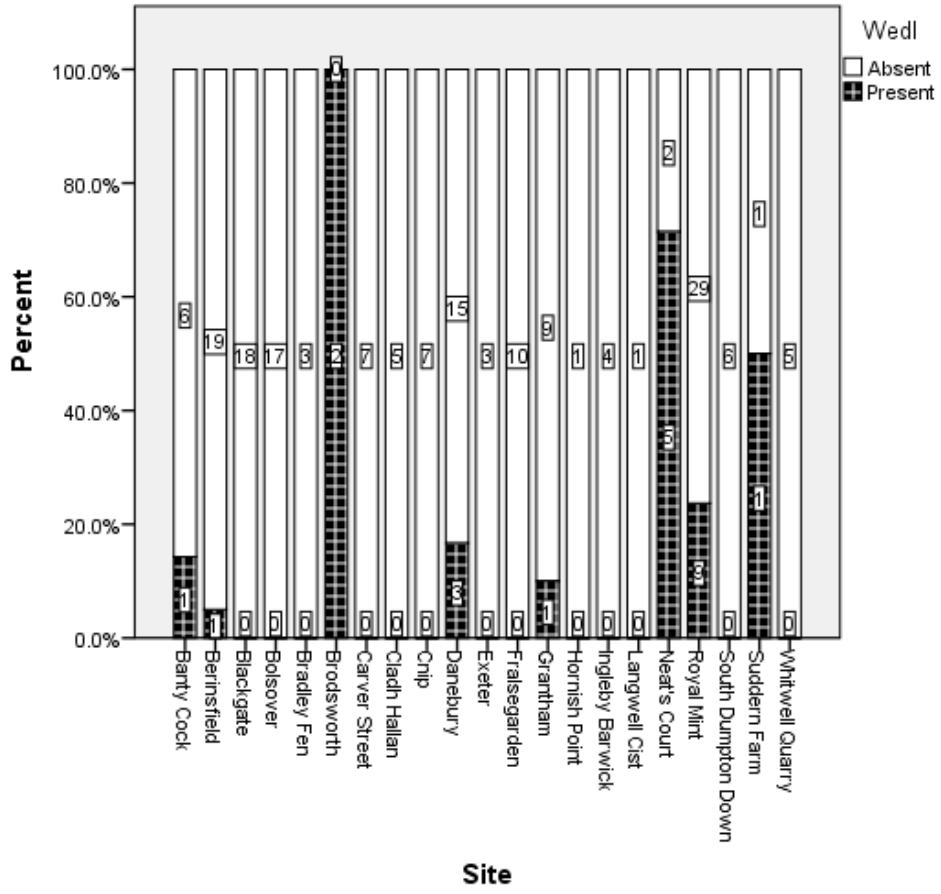

Figure 5.26: Proportional bar chart displaying the rates of Wedl tunnelling amongst site assemblages. Numbers on bars represent counts of cases.

5.2.6 Variation in the Perseverance of the Periosteal Surface

The periosteal surface had survived within 89% of the thin sections used in the current study. The persistence of the periosteal surface was tested against all explanatory variables within a binary logistic regression model. None of the explanatory variables had an effect on the presence of the periosteal surface in the first model (Appendix 1, page 595). The model was repeated without the Sex variable. None of the recorded variables had influenced the persistence of the periosteal surface in the second model (Table 5.9; Appendix 1, page 597).

The only explanatory variables that demonstrated a slightly elevated level of influence on periosteal preservation were Phase and Soil Type.

Variable	Outcome	Number of Samples	B	Wald	Significance (p-value)
Anoxia	Present/Absent	301	-18.965	0.000	0.998
Phase	Later Prehistoric/Historical	301	-0.471	0.394	0.547
Soil Type		301	-	7.901	0.095
	Clay	*159*	*20.579*	*0.000*	*0.999*
	Gravel	*65*	*39.483*	*0.000*	*0.999*
	Sand	*24*	*19.907*	*0.000*	*0.999*
	Silt	*35*	*18.548*	*0.000*	*0.999*
	Open	*18*	*0*	-	-
Cave	Cave/Non-Cave	301	-21.268	0.000	0.999
Black Death	Non-Black Death/Black Death	301	0.082	0.000	1.000
State	Articulated/Disarticulated	301	-0.262	0.165	0.684
Charnel	Non-Charnel/Charnel	301	0.084	0.011	0.916
Age Range	Overall	301		0.646	0.886
	Neonate	*31*	*-0.251*	*0.093*	*0.760*
	Child	*23*	*-0.463*	*0.341*	*0.559*
	Juvenile	*39*	*0.354*	*0.241*	*0.624*
	Adult	*208*	*0*	-	-

Table 5.9: Summary table of Parameter Estimates for the second binary logistic regression model of the persistence of the periosteal surface.

Variable	Outcomes	Number of Samples	B	Wald	Significance (p-value)
Phase	Later Prehistoric/Historical	301	-0.440	0.472	0.492
Soil Type	Overall	301	-	11.042	**0.026**
	Clay	*159*	*1.192*	*0.341*	*0.559*
	Gravel	*65*	*17.962*	*0.000*	*0.997*
	Sand	*24*	*-1.391*	*1.373*	*0.241*
	Silt	*35*	*-2.546*	*5.512*	***0.019***
	Open	*18*	*0*	-	-

Table 5.10: Summary table of Parameter Estimates for the third binary logistic regression of the persistence of the periosteal surface.

The regression model was run again with Phase and Soil Type as the only explanatory variables (Appendix 1, page 598). Only Soil Type influenced the persistence of the periosteal surface in the third model (Table 5.10). When the model was run once more with Soil Type as the only

explanatory variable, its influence on the survival of the periosteal surface became significant under the Holm-Bonferroni method (n=266, B=-0.477, Wald X^2=13.406, p=0.000; Appendix 1, page 599; Appendix 2). Bones from silt environments were more likely to have lost their periosteal surfaces (Figure 5.27). The Nagelkerke R-Squared figure for this model suggested that this variable accounted for 26.5% of variation in the survival of the periosteal surface.

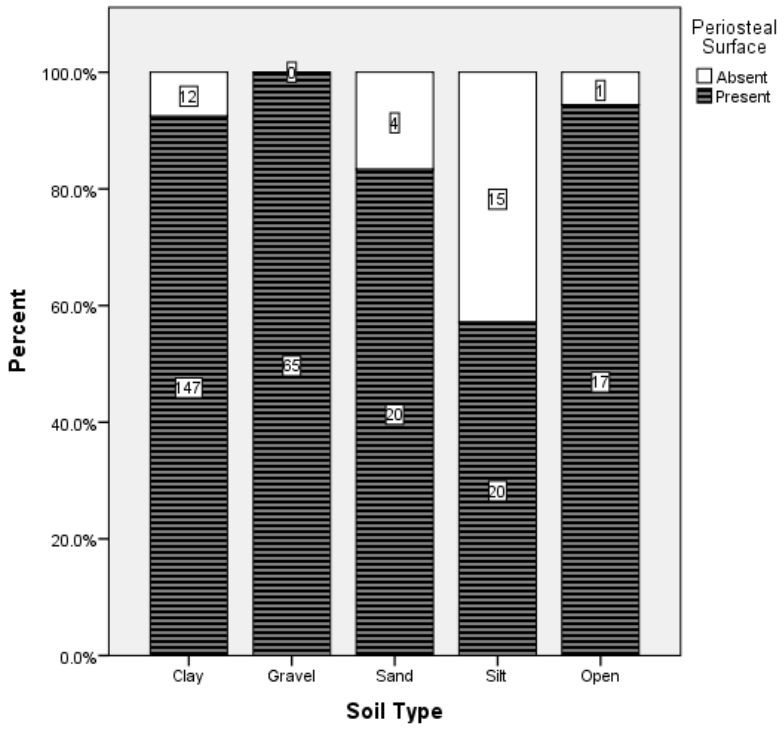

Figure 5.27: Proportional bar chart of the rates of survival of the periosteal surface amongst remains from different soil types. Numbers on bars represent counts of cases.

Variation in the persistence of the periosteal surface between separate sites was investigated to determine whether site-specific factors may have been responsible for periosteal survival. Pearson's X^2 tests of bones from silt and non-silt sites produced a p-values of less than 0.05 (Non-Silt: Bantycock n=7, Berinsfield n=20, Black Gate n=25, Bolsover, n=28, Bradley Fen n=3, Brodsworth n=2, Carsington Pasture Cave n=18, Carver Street n=9, Cladh Hallan n=5, Cnip n=7, Coronation Street, n=29, Exeter n=3, Frälsegården n=10, Grantham n=10, Hornish Point n=1, Ingleby Barwick n=4, Langwell Cist n=1, Neat's Court n=7, Royal mint n=38, York Barbican n=39, Fisher's Exact=10.563, p=0.015, Silt: n=266, Fisher's Exact=33.549, p=0.002). However, the Holm-Bonferroni method indicated that neither of these results could be accepted as significant (Appendix 2). The result of comparisons of periosteal surfaces between silt sites was close to the significance threshold within the Holm-Bonferroni model. Therefore, site-specific influences on persistence of the periosteal surface within silt contexts were still considered as

possible explanations for some of the variation in this parameter. Three out of the five sites that demonstrated silt burial contexts included bones that had lost their periosteal surfaces (Figure 5.28).

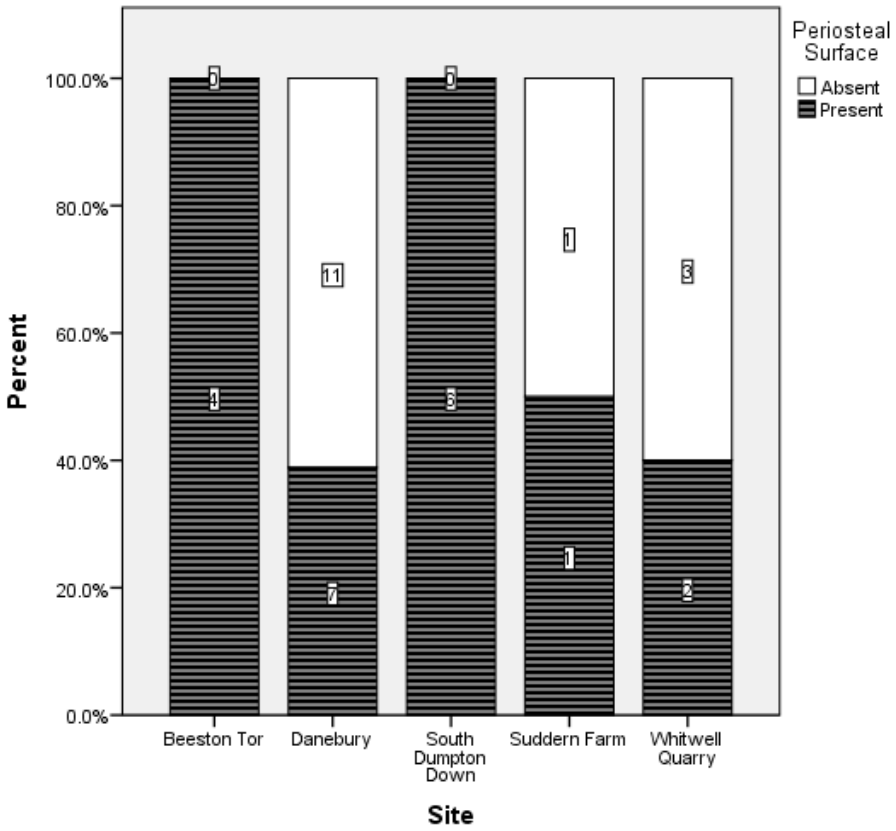

Figure 5.28: Proportional bar char displaying the rates of survival of the periosteal surface amongst bones from discrete sites that had been interred within silt environments. Numbers on bars represent counts of cases.

Many of the bone samples that had lost their periosteal surface originated from Iron Age contexts. There was a significant difference in the survival rate of the periosteal surface by Specific Phase (n=301, Fisher's Exact Test=40.288, p=0.000). Samples of Iron Age bones were more likely to have lost their periosteal surface (Figure 5.29). Periosteal loss appeared to have been partially influenced by factors specific to the Iron Age.

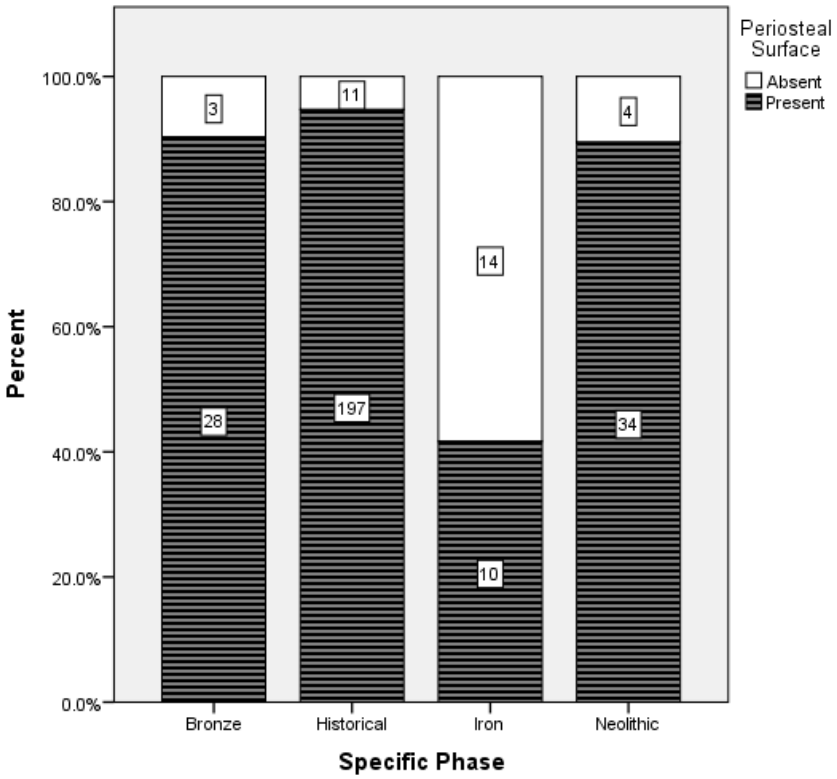

Figure 5.29: Rates of periosteal loss within samples of bone from different Specific Phase.

5.3 VISUAL DIAGENETIC PARAMETERS

This section will discuss the results from those diagenetic factors that had altered the appearance of bone microstructures (staining, inclusions and infiltrations) without causing any apparent loss of histological integrity. These variables were compared against one another initially to discern whether they represented different expressions of the same processes. An understanding of how these factors related to one another would benefit interpretations of the variables that influenced their appearance. This analysis would help to refine understanding of whether certain diagenetic features were the product of interactions between the bone and its external burial environment or other taphonomic processes.

Visual diagenetic changes have been linked with infiltrations of the bone by extraneous factors and occasionally with conditions that may have affected bodily putrefaction and bone bioerosion (Garland 1987; Grupe & Piepenbrink 1993; Schultz 1997; Shahack-Gross *et al.* 1997; Hollund *et al.* 2012). It would have been complicated to have tested the relationships between measures of bacterial bioerosion and visual diagenetic features within the regression models discussed above, as visual diagenetic features had not been recorded for all samples.

Therefore, the relationships between Whole OHI and visual diagenetic features were tested using Spearman's rho and Pearson's X^2 tests. Each visual diagenetic parameter was then incorporated into regression models along with relevant explanatory variables to identify the factors that were likely to have controlled their prevalence.

5.3.1 Interactions between Visual Diagenetic Parameters

5.3.1.1 Staining versus Inclusions.

Staining	Number of Samples	Orange Inclusions		Grey Inclusions	
		Spearman's rho	Significance (p-value)	Spearman's rho	Significance (p-value)
Orange	266	0.282	**0.000**	-0.278	**0.000***
Brown	266	0.019	0.761	-0.039	0.530
Yellow	266	0.004	0.950	0.070	0.257

Table 5.11: Summary of the results of Spearman's rho correlations of all types of staining against all types of inclusions.

Measures of each colour of microstructural staining were tested against the frequency of each colour of inclusions (Table 5.11). The frequency of orange staining demonstrated a significant positive relationship with the frequency of orange inclusions. Orange inclusions appeared infrequently within bones that were not stained or stained only superficially (Figure 5.30). Orange inclusions appeared frequently within bones that had been fairly or extensively stained. There was a significant negative correlation between the frequency of grey inclusions and orange staining. Grey inclusions only appeared within bones where orange staining was absent (Figure 5.31). None of the other colours of staining correlated with the remaining colours of inclusions.

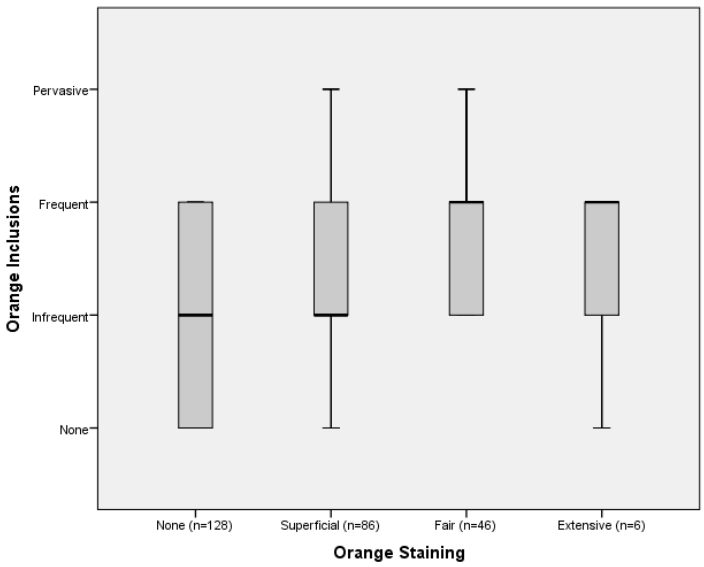

Figure 5.30: Box-and-whisker plot demonstrating the positive significant relationship between orange staining and orange inclusions.

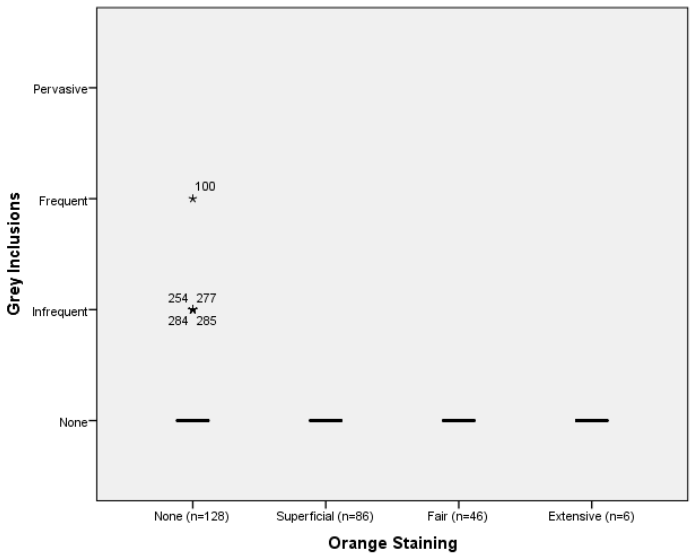

Figure 5.31: Box-and-whisker plot demonstrating the negative significant relationship between orange staining and grey inclusions.

5.3.1.2 Staining versus Infiltrations

Staining Colour	No. of Samples	Fisher's Exact Test	Significance (p-value)
Orange	266	71.400	**0.000***
Brown	266	4.907	0.140
Yellow	266	5.278	0.102

Table 5.12: Results of the statistical analysis of associations between staining colour and the presence of infiltration across the entire study sample.

Each colour of bone staining was tested against the presence of infiltrations. There was a significant relationship between the intensity of orange staining and the presence of infiltrations (Table 5.12). The proportion of bones that demonstrated infiltrations increased with the intensity of orange staining (Figure 5.32). There were no significant correlations between other colours of staining and infiltrations.

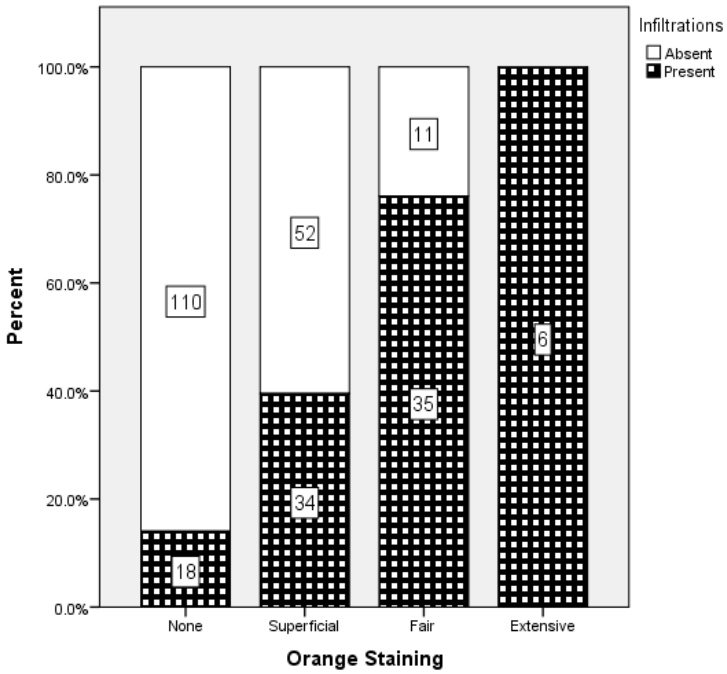

Figure 5.32: Proportional bar chart of the occurrence of infiltrations within bones that variably demonstrated orange microstructural staining. Numbers on bars represent counts of cases.

5.3.1.3 Inclusions versus Infiltrations

Inclusion Colour	No. of Samples	Fisher's Exact Test	Significance (p-value)
Orange	266	28.271	**0.000***
Grey	266	14.448	**0.000***

Table 5.13: Summary of the results of Pearson's X^2 tests of both colours of inclusions against the presence of infiltrations.

There was a significant relationship between the frequency of orange inclusions and presence of infiltrations (Table 5.13). The proportions of bone that included infiltrations increased with the frequency of orange inclusions (Figure 5.33). The frequency of orange inclusions did not

affect the proportion of bones that included infiltrations. The presence of infiltrations was dependent upon the presence of inclusions rather than their frequency. There was also a significant relationship between the frequencies of grey inclusions and the absence of infiltrations. Grey inclusions were only present within bones where infiltrations were absent (Figure 5.34).

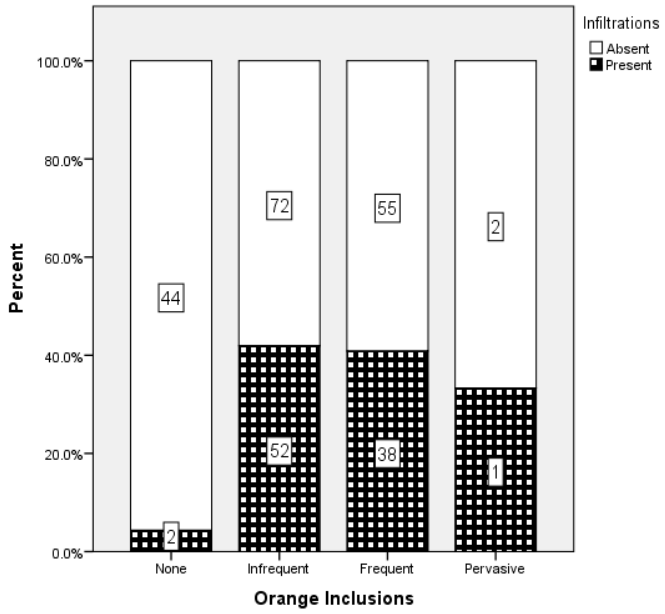

Figure 5.33: Proportional bar chart illustrating the occurrence of infiltrations within remains that demonstrated alternating frequencies of orange inclusions. Numbers on bars represent counts of cases.

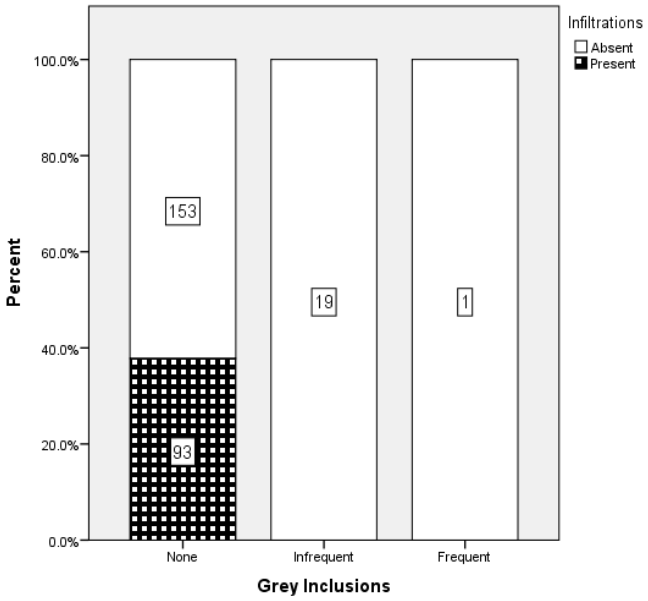

Figure 5.34: Proportional bar chart demonstrating occurrences of infiltrations within remains that demonstrated variable frequencies of grey inclusions. Pervasive grey inclusions were not observed within any samples. Numbers on bars represent counts of cases.

These comparisons of visual diagenetic changes indicated that orange staining, inclusions and infiltrations correlated significantly with one another and were likely to represent manifestations of similar processes. Correlations between measures of orange visual diagenetic changes were not as strong as those observed amongst measures of bone degradation. Orange staining inclusions and infiltrations were tested independently of one another in order to establish how their variation differed and how they might be used in isolation or in combination to reconstruct taphonomic histories of remains.

5.3.2 Staining

5.3.2.1 Variation in Orange Staining

Variable	Outcome	Number of Samples	Estimate	Wald	Significance (p-value)
Anoxia	Absent	240	-0.911	4.341	**0.037**
	Present	26	0	-	-
Phase	Later Prehistoric	93	-0.269	0.344	0.557
	Historical	173	0	-	-
Soil Type	Clay	124	4.0008	9.354	**0.002**
	Gravel	65	4.796	12.851	**0.000***
	Sand	24	3.519	7.058	**0.008**
	Silt	35	2.072	3.634	0.057
	Open	18	0		
Cave	Non-Cave	244	-3.425	8.889	**0.003**
	Cave	22	0		
Black Death	Non Black Death	241	0.684	2.012	0.156
	Black Death	25	0	-	-
State	Articulated	203	0.992	2.907	0.088
	Disarticulated	63	0	-	-
Charnel	Non-Charnel	213	1.235	8.446	**0.004**
	Charnel	53	0	-	-
Age Range	Neonate	29	0.131	0.084	0.771
	Child	20	-0.195	0.162	0.687
	Juvenile	24	-0.184	0.157	0.692
	Adult	193	0	-	-

Table 5.14: Summary of the Parameter Estimates for the second ordinal regression model for orange staining.

Forty-five-per-cent of all samples demonstrated orange staining, which represented 78% of all samples that had been stained. Orange staining was the colour found most often within the study sample. Orange staining was usually superficial (62% of orange-stained samples) or fair (33%) and was rarely extensive (4%). The intensity of orange staining was tested against Whole OHI to investigate whether it was reflective of environments that affected bacterial bioerosion. There was no significant association between the extent of orange staining and Whole OHI (n=266, Spearman's rho=0.026, p=0.678). The intensity of orange staining was tested against all recorded explanatory variables within an ordinal regression model. The first model did not identify any of the explanatory variables as having influenced levels of orange staining (Appendix 1, page 601). The ordinal regression was run again without the Sex variable.

Soil Type, Cave Deposition, Anoxic Environment and Charnel Deposits had influenced orange staining within the second regression model (Table 5.14; Appendix 1, page 603). The Wald X^2 scores of State and Anoxic Environment produced p-values that were close to 0.05. The ordinal regression was run again with these five variables. All explanatory variables were influential within the third model (Table 5.15; Appendix 1, page 605). The Nagelkerke R-Squared for this regression model indicated that 25.2% of variation in orange staining was explained by these explanatory variables.

However, only one outcome within Soil Type could be considered to have had a significant effect on orange staining at when the Holm-Bonferroni method was applied (Appendix 2). The influence of the Charnel Deposits was close to significant within the Holm-Bonferroni method. The regression model was run again with these two variables. Only Soil Type demonstrated a significant level of influence on orange staining within this fourth model (Table 5.16; Appendix 1, page 606). The significant influence of Soil Type was maintained when this explanatory variable was placed in an ordinal regression of orange staining by itself (Table 5.17; Appendix 1, page 607). The Nagelkerke Pseudo R-Squared value indicated that Soil Type described 16.7% of the variation in orange staining.

Variable	Outcome	Number of Samples	Estimate	Wald	Significance (p-value)
Anoxia	Absent	240	-0.884	4.214	**0.041**
	Present	26	0	-	-
Soil Type	Clay	124	4.121	10.341	**0.001**
	Gravel	65	4.644	12.888	**0.000***
	Sand	24	3.577	7.433	**0.006**
	Silt	35	2.037	3.586	0.058
	Open	18	0	-	-
Cave	Non-Cave	244	-3.515	5.491	**0.019**
	Cave	22	0	-	-
State	Articulated	203	1.195	5.491	**0.019**
	Disarticulated	63	0	-	-
Charnel	Non-Charnel	213	1.212	10.559	**0.001**
	Charnel	53		-	-

Table 5.15: Summary of the Parameter Estimates from the third ordinal regression of orange staining.

Variable	Outcome	Number of Samples	Estimate	Wald	Significance (p-value)
Soil Type	Clay	124	1.796	8.803	0.003
	Gravel	65	2.269	14.158	**0.000***
	Sand	24	0.877	1.657	0.198
	Silt	35	-0.370	0.274	0.601
	Open	18	0	-	-
Charnel	Non-Charnel	213	0.900	6.629	0.010
	Charnel	53		-	-

Table 5.16: Summary of the Parameter Estimates from the fourth ordinal regression of orange staining.

Variable	Outcome	Number of Samples	Estimate	Wald	Significance (p-value)
Soil Type	Clay	124	1.376	5.665	0.017
	Gravel	65	2.248	13.899	**0.000***
	Sand	24	0.874	1.642	0.200
	Silt	35	-0.369	0.272	0.602
	Open	18	0	-	-

Table 5.17: Summary of the Parameter Estimates from the fifth ordinal regression of orange staining.

The parameter estimates from the regression models indicated that gravel environments had the largest overall effect on the extent of orange staining. Bones from gravel environments were more likely to demonstrate higher levels of orange staining. Orange staining was usually

absent from remains recovered from silt and open environments, absent or only superficial within remains from sands and slightly more extensive within remains clay (Figure 5.35).

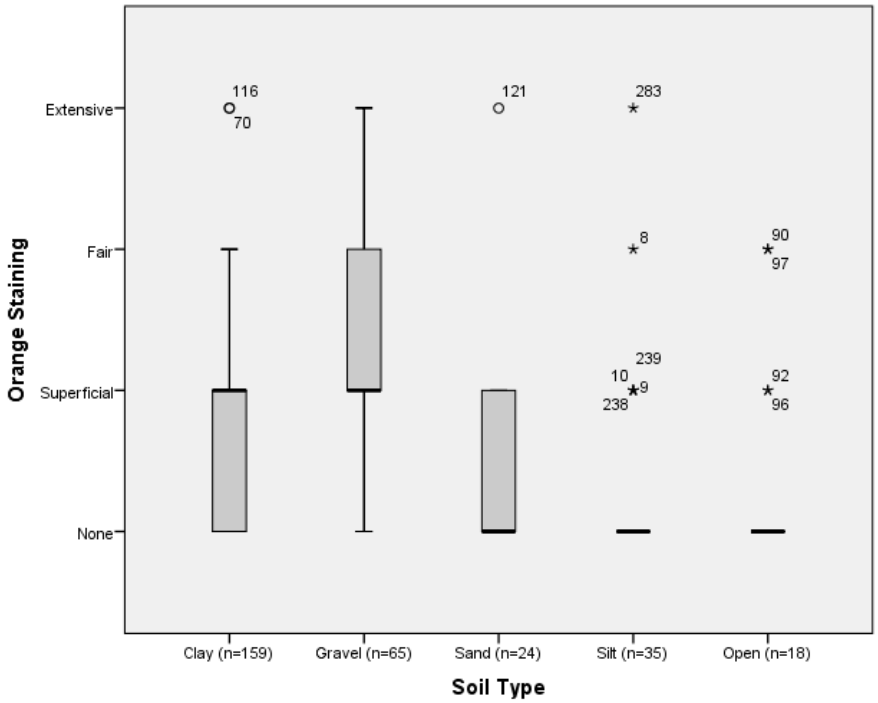

Figure 5.35: Box-and-whisker plot demonstrating the distribution of orange staining amongst bones recovered from different types of soils.

The results from the Charnel Deposits were close to the significant threshold within the Holm-Bonferroni method (Appendix 2). All of the charnel remains were recovered from clay environments. The parameter estimate indicated that charnel samples demonstrated lower levels of orange staining than Historical samples that were recovered in articulation. This patterning was confirmed within comparisons of charnel and non-charnel remains from clay environments (Figure 5.36).

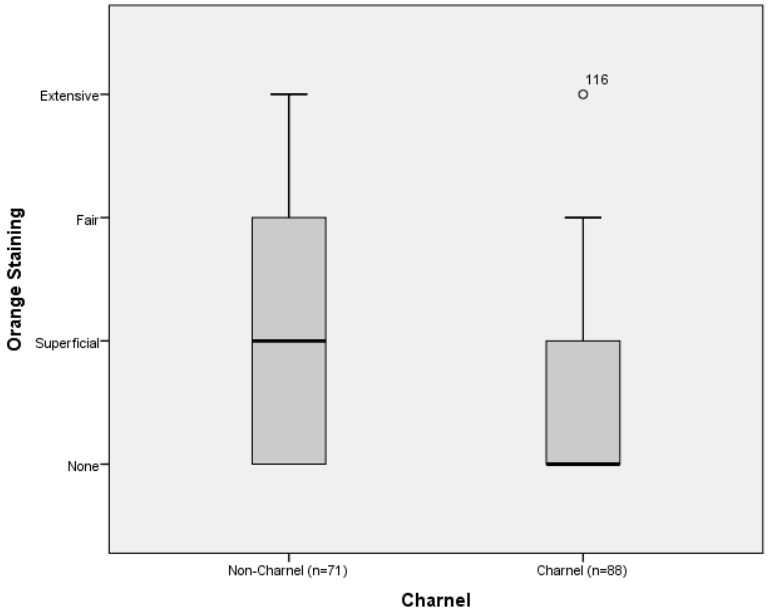

Figure 5.36: Box-and-whisker plot of the distribution of orange staining amongst charnel and non-charnel remains from clay burial contexts.

It was possible that site-specific influences may have affected the extent of orange microstructural staining. Kruskal-Wallis tests of orange staining amongst different site assemblages from separate soil types produced p-values of less than 0.05 (Table 5.18). Samples of bone from the Open Soil Type category were not included as they all originated from a single site. The Holm-Bonferroni method determined that only the result from the clay site assemblages was significant (Appendix 2). Orange staining amongst site assemblages from clays was highly variable (Figure 5.37). Orange staining was only extensive within remains from Carver Street and completely absent from bones recovered from Frälsegården and Brodsworth. There was no obvious patterning to the orange staining within these assemblages, which suggested that unrecorded site-specific factors were partly responsible for variation.

Burial Soil	No. of samples	Kruskal-Wallis X^2	Significance (p-value)
Clay	71	43.961	**0.000***
Gravel	65	11.147	**0.011**
Sand	24	10.722	**0.030**
Silt	31	13.313	**0.010**

Table 5.18: Summary of the results from the Kruskal-Wallis analysis of differences in levels of orange staining between site assemblages whilst controlling for Soil Type.

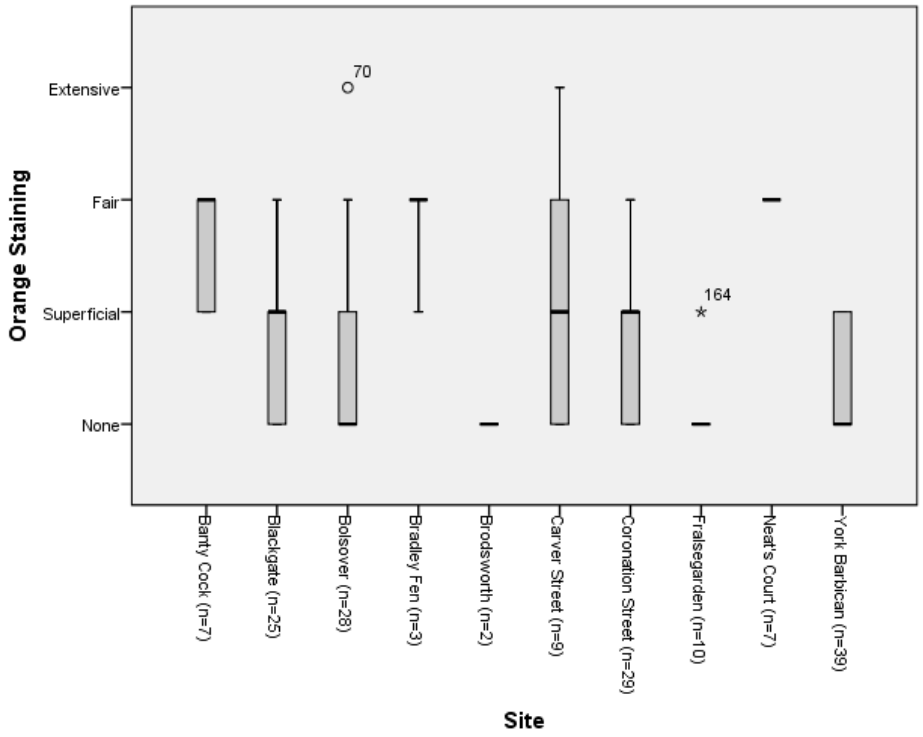

Figure 5.37: Box-and-whisker plot of the distribution of orange staining amongst site assemblages that had been interred within clay.

5.3.2.2 Variation in Brown Staining

Only 8% of the whole study sample demonstrated instances of brown staining, which represented 13% of stained bones. Brown staining was usually only superficial (65% of brown-stained bones) or fair (30%), and was rarely extensive (4%).The intensity of brown staining was tested against Whole OHI to determine whether this feature was indicative of a burial environment or process that interfered with microbial bioerosion of bone. The correlation between the intensity of brown staining and Whole OHI score produced a p-value that was below 0.05 (n=266, Spearman's rho=0.138, p=0.024). However, the Holm-Bonferroni method indicated that this result could not be accepted as significant (Appendix 2).

All potentially explanatory variables were tested against the intensity of brown microstructural staining within an ordinal regression model. Phase was the only variable that had a significant influence on the extent of brown staining within the first model (Appendix 1, page 609). The Sex variable was removed and the ordinal regression was performed again.

Variable	Outcome	Number of Samples	Estimate	Wald	Significance (p-value)
Anoxia	Absent	240	-0.134	0.032	0.858
	Present	26	0	-	-
Phase	Later Prehistoric	93	2.153	7.758	**0.005**
	Historical	173	0	-	-
Soil Type	Clay	124	0.701	0.000	1.000
	Gravel	65	1.891	0.000	0.999
	Sand	24	2.245	0.000	0.999
	Silt	35	0.258	0.000	1.000
	Open	18	0	-	-
Cave	Non-Cave	244	14.478	-	**-**
	Cave	22	0	-	-
Black Death	Non Black Death	241	-0.229	0.054	0.817
	Black Death	25	0	-	-
State	Articulated	203	0.661	0.768	0.381
	Disarticulated	63	0	-	-
Charnel	Non-Charnel	213	-1.909	4.519	**0.034**
	Charnel	53	-	-	-
Age Range	Neonate	29	0.667	0.495	0.482
	Child	20	-14.563	0.000	0.990
	Juvenile	24	0.104	0.022	0.882
	Adult	193	0	-	-

Table 5.19: Summary of the Parameter Estimates from the second ordinal regression model for brown staining.

Phase and Charnel Deposits influenced the extent of brown staining in the second ordinal regression model (Table 5.19; Appendix 1, page 611). All variables apart from Phase and Charnel were removed and the model was run once more. Neither variable had an influence on the occurrence of brown staining within this third model (Table 5.20; Appendix 1, page 613). It could not be stated with certainty that either of these variables had any effect on brown staining, The failure of this model suggested that brown staining appeared too infrequently and sporadically for its variation to be characterised using regression models.

Variable	Outcome	Number of Samples	Estimate	Wald	Significance (p-value)
Phase	Later Prehistoric	93	0.840	2.485	0.115
	Historical	173	0	-	-
Charnel	Non-Charnel	213	-1.002	2.911	0.088
	Charnel	53	-	-	-

Table 5.20: Summary of Parameter Estimates for the third ordinal regression model of brown staining.

It was possible that local site-specific influences may have determined the intensity of microstructural brown staining. Bones from most sites did not demonstrate any brown staining. Brown stained bones only appeared with frequency within bones from Ingleby Barwick, Frälsegården, Cnip and Langwell Cist, which were all Later Prehistoric sites. A Kruskal-Wallis test of the differences in distributions of brown staining between site assemblages produced a p-value less than 0.05 (n=266, Kruskal-Wallis X^2=44.128, p=0.007). However, the Holm-Bonferroni method indicated that this result was not significant (Appendix 2). The result from this test was close to the threshold of significance within the Holm-Bonferroni method and it was possible that the extent of brown staining was linked to site-specific factors (Figure 5.38). Brown staining appeared too sporadically for its variation to be characterised, and the factors that may have influenced its occurrence would have to be discussed qualitatively.

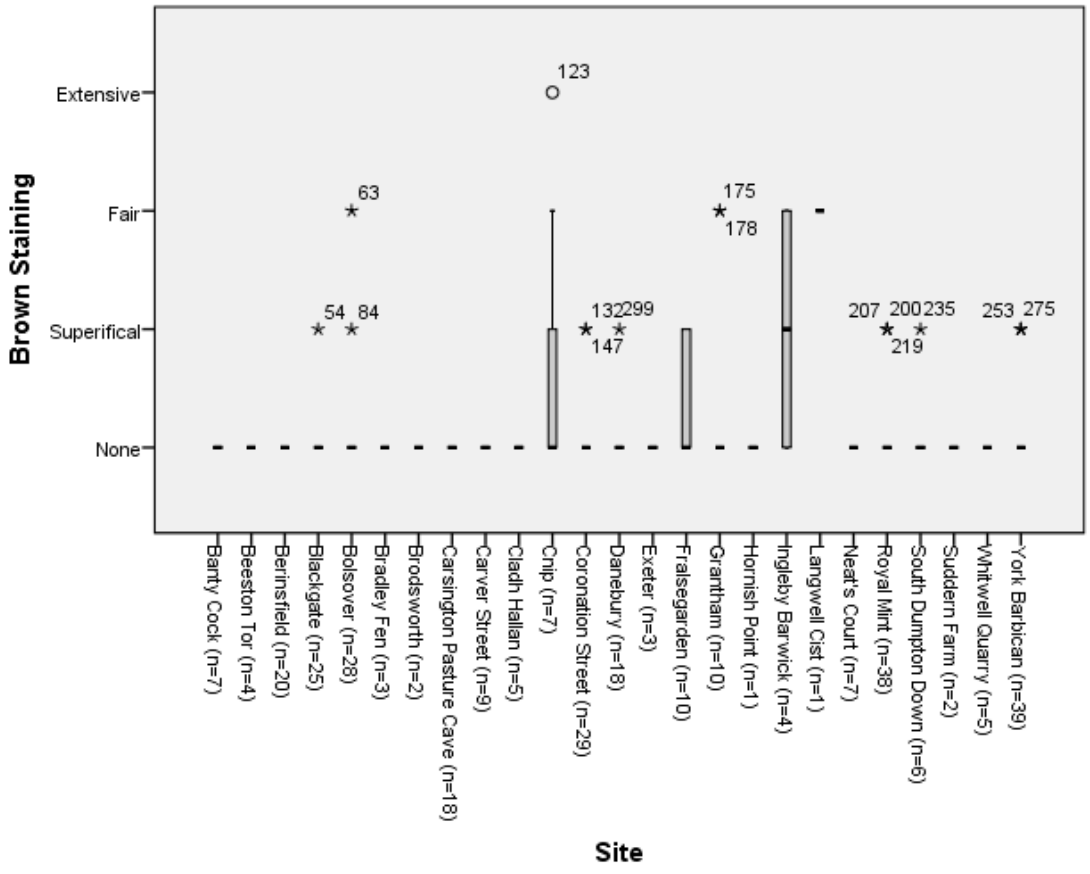

Figure 5.38: Box-and whisker plot of the extent of brown microstructural staining amongst the entire study sample grouped by site assemblage.

5.3.2.3 Variation in Yellow Staining

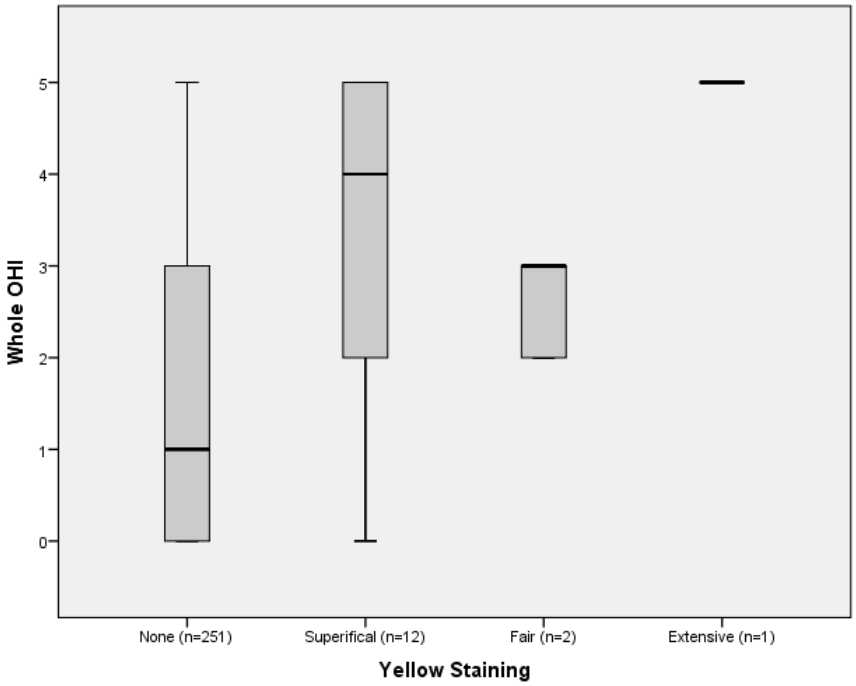

Figure 5.39: Box-and-whisker plot of the distributions of Whole OHI scores amongst remains that demonstrated varying levels of yellow microstructural staining.

Only 5% of the study sample demonstrated yellow staining, which made up 9% of the total number of stained specimens. Yellow staining was usually only superficial (80% of yellow-stained samples) and occasionally fair (13%). Yellow staining was rarely extensive (7%). The positive correlation between Whole OHI score and the intensity of yellow staining produced a p-value that was lower than 0.05 (n=266, Spearman's rho=0.211, p=0.001). The Holm-Bonferroni correction determined that this result was not significant (Appendix 2). The p-value for this result was close to the threshold of significance within the Holm-Bonferroni method. Yellow staining was mostly absent from bones with low Whole OHI scores, but was more intense amongst those that were histologically well-preserved (Figure 5.39). However, yellow staining was rarer than brown staining and it was unlikely that any correlation would have significantly affected the overall results from measures of bacterial bioerosion. The possible effect yellow staining on histological preservation is explored in later chapters.

Variable	Outcome	Number of Samples	Estimate	Wald	Significance (p-value)
Anoxia	Absent	240	-0.391	0.181	0.670
	Present	26	0	-	-
Phase	Later Prehistoric	93	0.052	0.002	0.968
	Historical	173	0	-	-
Soil Type	Clay	124	-14.275	92.528	**0.000***
	Gravel	65	-28.403	0.001	0.981
	Sand	24	-13.016	91.798	**0.000***
	Silt	35	-14.675	101.347	**0.000***
	Open	18	0	-	-
Cave	Non-Cave	244	14.369	-	**-**
	Cave	22	0	-	-
Black Death	Non Black Death	241	-16.168	0.000	0.989
	Black Death	25	0	-	-
State	Articulated	203	-0.835	0.434	0.510
	Disarticulated	63	0		-
Charnel	Non-Charnel	213	-1.014	0.848	0.357
	Charnel	53	0	-	-
Age Range	Neonate	29	0.058	0.002	0.962
	Child	20	-14.197	0.000	0.992
	Juvenile	24	0.191	0.046	0.831
	Adult	193	0	-	-

Table 5.21: Summary of Parameter Estimates from the second ordinal regression of yellow staining.

All potentially explanatory variables were tested against the intensity of yellow staining within an ordinal regression model. None of the explanatory variables were found to have enacted an influence on the severity of yellow staining in the first model (Appendix 1, page 614). Sex was removed and the remaining explanatory variables were tested again. The second model identified that only Soil Type had a significant influence on yellow staining (Table 5.21; Appendix 1, page 616). The Nagelkerke Pseudo R-squared value indicated that this model accounted for 13.5% of variation in yellow staining. However, Soil Type no longer demonstrated a significant influence on yellow staining when it was placed in an ordinal regression model by itself (Table 5.22; Appendix 1, page 618). None of the variables included within the regression demonstrated a consistent significant influence on yellow microstructural staining.

Variable	Outcome	Number of Samples	Estimate	Wald	Significance (p-value)
Soil Type	Clay	124	-0.144	0.017	0.897
	Gravel	65	0.138	0.014	0.905
	Sand	24	0.869	0.518	0.471
	Silt	35	-0.654	0.206	0.650
	Open	18	0	-	-

Table 5.22: Summary of the Parameter Estimates from the fourth ordinal regression model of yellow staining.

It was possible that the intensity of yellow staining was influenced by site-specific taphonomic events. When soil type was controlled there were no significant differences in yellow staining between bones from separate site assemblages (Table 5.23). It was possible that the occurrence of yellow staining was too low to produce viable results. The influencers of yellow staining would have to be discerned through more detailed investigation into each yellow-stained bone's specific environmental and taphonomic circumstances.

Burial Soil	No. of samples	Kruskal-Wallis X^2	Significance (p-value)
Clay	124	9.844	0.363
Sand	65	5.122	0.482
Gravel	65	2.979	0.395
Silt	35	0.944	0.918

Table 5.23: Summary of the results from statistical tests of differences in levels of yellow staining separate site assemblages whilst controlling for soil type.

5.3.3 Inclusions

5.3.3.1 Variation in Orange Inclusions

Orange inclusions were present within 73% of bones samples, which represented 85% of all samples that demonstrated these features. Where they appeared, orange inclusions were usually infrequent (56%) or frequent (42%) and rarely extensive (1%). There was no statistically significant association between the extent of orange inclusions and Whole OHI Score (n=266, Spearman's rho=0.104, p=0.092).

Variable	Outcome	Number of Samples	Estimate	Wald	Significance (p-value)
Anoxia	Absent	240	-0.652	2.098	0.147
	Present	26	0	-	-
Phase	Later Prehistoric	93	0.392	0.706	0.401
	Historical	173	0	-	-
Soil Type	Clay	124	2.890	5.631	**0.018**
	Gravel	65	2.100	2.865	0.091
	Sand	24	2.980	5.915	**0.015**
	Silt	35	0.731	0.462	0.497
	Open	18	0	-	-
Cave	Non-Cave	244	-2.147	4.120	**0.042**
	Cave	22	0	-	-
Black Death	Non Black Death	241	-0.790	2.491	0.115
	Black Death	25	0	-	-
State	Articulated	203	1.042	4.314	**0.038**
	Disarticulated	63	0	-	**-**
Charnel	Non-Charnel	213	1.209	7.938	**0.005**
	Charnel	53	0	-	**-**
Age Range	Neonate	29	0.984	4.290	**0.038**
	Child	20	0.141	0.089	0.766
	Juvenile	24	0.570	1.744	0.187
	Adult	193	0	-	-

Table 5.24: Summary of Parameter Estimates from the second ordinal regression of orange inclusions.

The occurrence of orange inclusions was tested against all recorded variables within an ordinal regression model. Only particular outcomes within Soil Type had an influence on this parameter within the first model (Appendix 1, page 619). The Sex variable was removed and the remainder of the explanatory variables were included within the second round of testing. Soil Type, Charnel Deposits, State of Articulation, Age Range and Cave Deposition had all influenced the frequency of orange inclusions in the second regression model (Table 5.24; Appendix 1, page 621). The regression was run again using only influential variables. Age Range no longer had an influence on orange inclusions in this third model (Appendix 1, page 623). Age Range was removed and the remaining explanatory variables were tested again. All of the remaining explanatory variables maintained p-values of less than 0.05, although only Charnel had a significant influence when the Holm-Bonferroni correction was considered (Table 5.25; Appendix 1, page 625; Appendix 2). The p-value for one outcome within soil type was close to significant within the Holm-Bonferroni method. These two variables were included within a fifth ordinal regression model (Table 5.26) (Appendix 1, page 626). The Charnel remains

maintained a significant influence on orange inclusions when the Holm-Bonferroni correction was considered. The p-values related to the influence of Soil Types were reduced in size but were not significant as defined by the Holm-Bonferroni method (Appendix 2). The significant influence of Charnel remains was lost when this explanatory variable was placed by itself within an ordinal regression of orange inclusions (n=266, parameter estimate=0.437, Wald X^2=2.274, p=0.132; Appendix 1, page 627). None of the explanatory variables demonstrated a consistent significant relationship with the extent of orange inclusions.

Variable	Outcome	Number of Samples	Estimate	Wald	Significance (p-value)
Soil Type	Clay	124	3.018	6.496	**0.011**
	Gravel	65	2.113	3.151	0.076
	Sand	24	2.968	6.048	**0.014**
	Silt	35	0.781	0.545	0.461
	Open	18	0	-	-
Cave	Non-Cave	244	-2.257	4.758	**0.029**
	Cave	22	0	-	-
State	Articulated	203	0.952	4.749	**0.029**
	Disarticulated	63	0	-	**-**
Charnel	Non-Charnel	213	1.372	14.341	**0.000***
	Charnel	53	0	-	**-**

Table 5.25: Summary of Parameter Estimates from the fourth ordinal regression model of orange inclusions.

Variable	Outcome	Number of Samples	Estimate	Wald	Significance (p-value)
Soil Type	Clay	124	1.578	9.400	**0.002**
	Gravel	65	0.773	2.282	0.131
	Sand	24	1.256	4.362	**0.037**
	Silt	35	-0.895	2.575	0.109
	Open	18	0	-	-
Charnel	Non-Charnel	213	1.245	12.235	**0.000***
	Charnel	53	0	-	**-**

Table 5.26: Summary of the Parameter Estimates from the fifth ordinal regression model of orange inclusions.

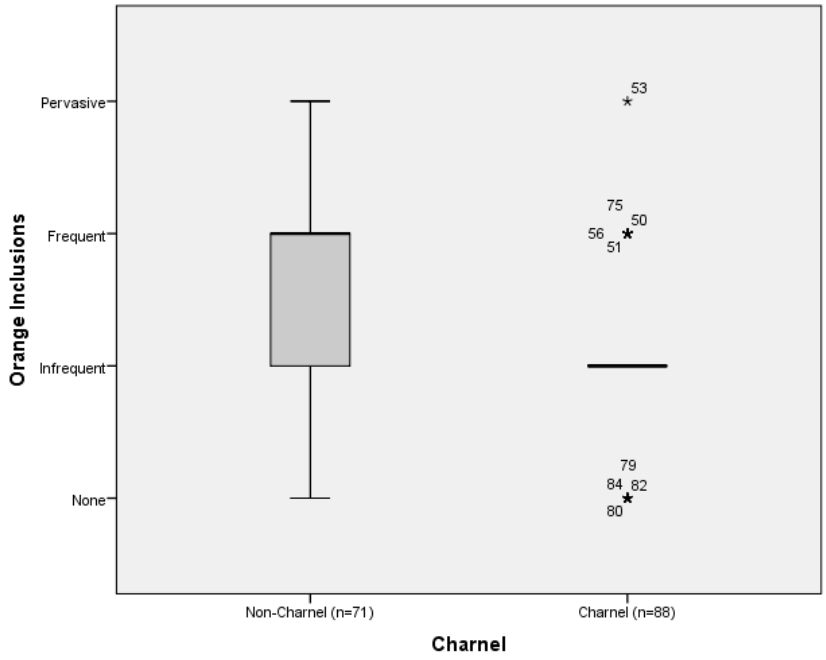

Figure 5.40: Box-and-whisker plot of the distribution of orange inclusions amongst bones that were variably recovered from charnel deposits within clay contexts.

The relationship between orange inclusions and Charnel Deposit persisted for longest amongst the ordinal regressions. It was salient to examine the nature of the potential relationship between these two variables. Charnel bones were more likely to demonstrate lower levels of orange inclusions than remains recovered as part of articulated skeletons (Figure 5.40). However, the range of orange inclusion frequency was similar between these two groups.

The potential relationship between orange inclusions and Soil Type was also explored. When the charnel remains were excluded, bones obtained from silt and open contexts demonstrated lower levels of orange inclusions than bones from all other types of deposits (Figure 5.41). Distributions of orange inclusions amongst remains from clays and sands were similarly high, although bones that demonstrated pervasive inclusions were only recovered from clay contexts. Distributions of orange inclusions amongst bones from gravel sites lay between these two extremes.

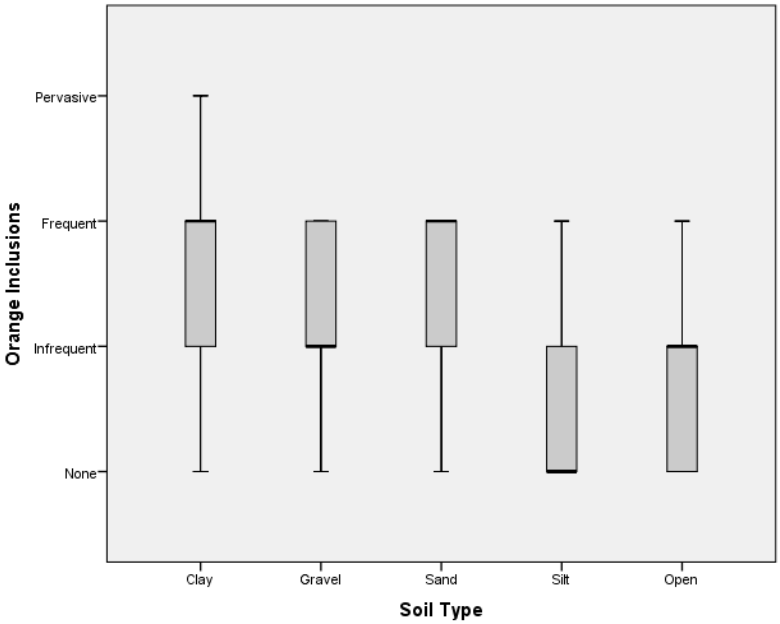

Figure 5.41: Box-and-whisker plot of the distribution of orange inclusions amongst bones recovered from different soil types (charnel bones were excluded).

It was possible that unrecorded site-specific factors had some effect on the extent to which inclusions were deposited within the natural porosities of bones samples. However Kruskal-Wallis tests of orange inclusion scores between different site assemblages, whilst controlling for the effects soil type and charnel deposits, found that variation was only significant within site assemblages recovered from silt (Table 5.27). Orange inclusions appeared more often within remains from South Dumpton Down, Whitwell Quarry and Beeston Tor (Figure 5.42). Levels of orange inclusions within these remains were similar to those from the rest of the study sample. The lower levels of orange inclusions within remains from silts were mostly attributable to the remains from Danebury and Suddern Farm.

Burial Soil	No. of samples	Kruskal-Wallis X^2	Significance (p-value)
Clay	71	9.707	0.206
Gravel	65	7.930	**0.047**
Sand	24	6.922	0.140
Silt	31	21.493	**0.000***

Table 5.27: Summary table of statistical tests of the differences in levels of orange inclusions between separate site assemblages whilst controlling for soil type.

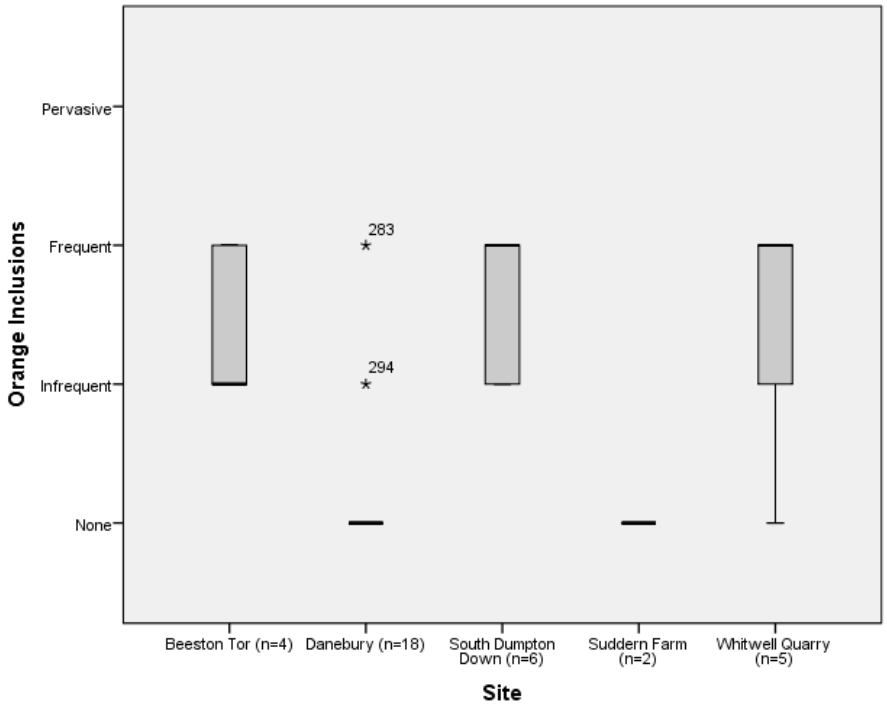

Figure 5.42: Box-and-whisker plot of the distribution of orange inclusions amongst separate site assemblages that had been deposited within silt.

5.3.3.2 Variation in Grey Inclusions

Grey inclusions were identified within 6% of all samples, which represented 15% of all samples that demonstrated inclusions. Grey inclusions almost always appeared infrequently (95%) and occurred frequently in only one sample (5%). There was no statistically significant relationship between the occurrence of grey inclusions and Whole OHI score (n=266, Spearman's rho=0.035, p=0.057).

The occurrence of grey inclusions were tested against all recorded explanatory variables within an ordinal regression model. None of the explanatory variables had an influence on the frequencies of grey inclusions within the first model (Appendix 1, page 629). Sex was removed and the ordinal regression was repeated. Only outcomes within Soil Type influenced grey inclusions within the second model (Table 5.28; Appendix 1, page 631). Values within Age Range and State demonstrated slightly higher levels of influence than other variables. The ordinal regression was run again with Soil Type, Age Range and State. Only Soil Type influenced the extent of grey inclusions within this third model (Table 5.29; Appendix 1, page 633). The only significant outcome of Soil Type was a silt context. The Nagelkerke Pseudo R-Squared result indicated that this model accounted for 69.5% of the variation in grey inclusions. However, when Soil Type was placed by itself within a further regression model, none of the

outcomes maintained a significant influence on the extent of grey inclusions (Table 5.30; Appendix 1, page 634). The Nagelkerke Pseudo R-Squared indicated that Soil Type by itself described 49.8% of the variation in grey inclusions.

Variable	Outcome	Number of Samples	Estimate	Wald	Significance (p-value)
Anoxia	Absent	240	14.716	0.000	0.992
	Present	26	0	-	-
Phase	Later Prehistoric	93	0.086	0.000	1.000
	Historical	173	0	-	-
Soil Type	Clay	124	-34.146	0.001	0.981
	Gravel	65	-34.778	0.000	0.986
	Sand	24	-34.185	0.000	0.986
	Silt	35	-15.703	207.440	**0.000***
	Open	18	0	-	-
Cave	Non-Cave	244	18.147	-	**-**
	Cave	22	0	-	-
Black Death	Non Black Death	241	-0.273	0.000	1.000
	Black Death	25	0	-	-
State	Articulated	203	0.969	1.243	0.265
	Disarticulated	63	0	-	**-**
Charnel	Non-Charnel	213	-14.865	0.000	0.989
	Charnel	53	0	-	**-**
Age Range	Neonate	29	-12.694	0.000	0.992
	Child	20	1.301	0.840	0.359
	Juvenile	24	0.269	0.072	0.789
	Adult	193	0	-	-

Table 5.28: Summary of the Parameter Estimates from the second ordinal regression of grey inclusions.

Variable	Outcome	Number of Samples	Estimate	Wald	Significance (p-value)
Soil Type	Clay	124	-2.531	2.877	0.090
	Gravel	65	-17.820	0.000	0.992
	Sand	24	-17.382	0.000	0.995
	Silt	35	2,257	4.335	**0.037**
	Open	18	0	-	-
State	Articulated	203	1.311	2.409	0.121
	Disarticulated	63	0	-	**-**
Age Range	Neonate	29	-15.842	0.000	0.995
	Child	20	0.217	0.041	0.839
	Juvenile	24	0.533	0.276	0.599
	Adult	193	0	-	-

Table 5.29: Summary of the Parameter Estimates from the third ordinal regression of grey inclusions.

Variable	Outcome	Number of Samples	Estimate	Wald	Significance (p-value)
Soil Type	Clay	124	-1.337	1.181	0.981
	Gravel	65	-19.348	0.000	0.986
	Sand	24	-19.348	-	0.986
	Silt	35	2.668	6.360	**0.012**
	Open	18	0	-	-

Table 5.30: Summary of the Parameter Estimates from the fourth ordinal regression of grey inclusions.

None of the explanatory variables had a consistent significant influence on grey inclusions. However, the effect of Soil Type was explored further, as the relationship between this variable and grey inclusions approached significance. Remains from silt contexts were more likely to demonstrate higher levels of grey inclusions (Figure 5.43). Grey inclusions were mostly absent within bones from other soil types.

It was possible that site-specific influences may have influenced the occurrence of grey inclusions. Frequencies of grey inclusions were tested separately between sites that included silt and non-silt environments. There was a significant difference in the distributions of grey inclusions amongst remains from different sites that had been interred within a silt environment, but no differences between those assemblages that had not been inhumed within silt (Table 5.31). Grey inclusions were only present within silt-deposited remains from Danebury and Suddern Farm (Figure 5.44). This trend was the reverse of what was observed with regards to orange inclusions amongst silt-deposited site assemblages.

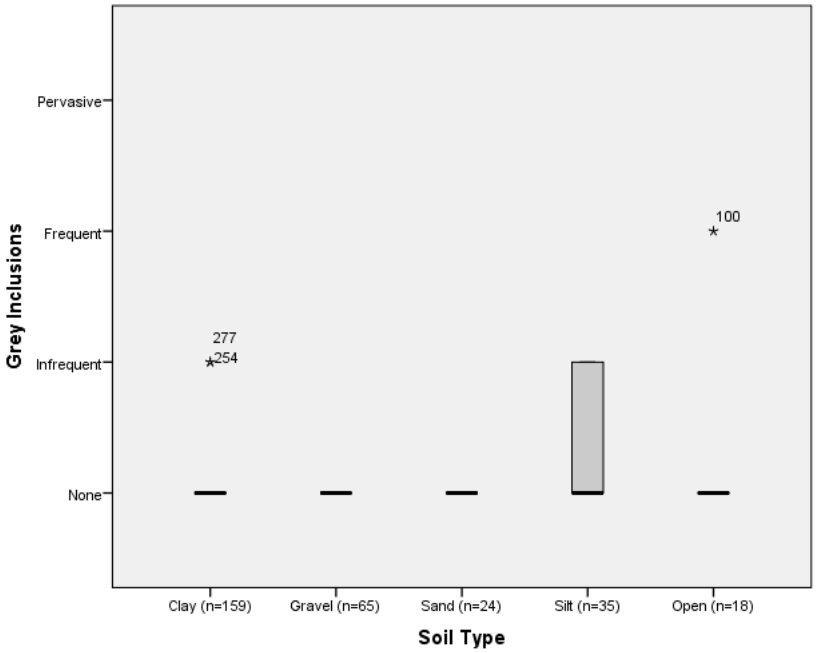

Figure 5.43: Box-and-whisker plot of the distribution of grey inclusions amongst remains recovered from different types of soils.

Burial Soil	No. of samples	Kruskal-Wallis X^2	Significance (p-value)
Silt	35	24.278	**0.000***
Non-Silt	231	18.475	0.491

Table 5.31: Summary of statistical tests of the distributions of grey inclusions amongst separate site assemblages variably recovered from silt.

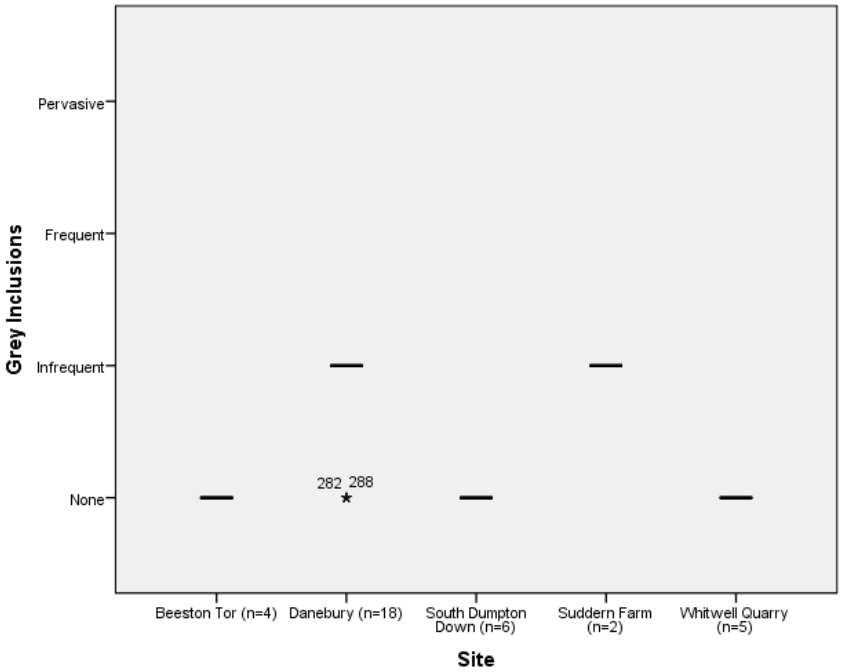

Figure 5.44: Box-and-whisker plot of the distribution of grey inclusions amongst site assemblages that had been interred within silt.

5.3.4 Infiltrations

Orange Infiltrations were present within 31% of the study sample. Pearson's X^2 test of the presence of infiltrations amongst remains that demonstrated different Whole OHI scores produced a p-value of less than 0.05 (n=266, Pearson's X^2=13.698, p=0.017). However, the Holm-Bonferroni method indicated that this result was not significant (Appendix 2). The presence of orange infiltrations was tested against all potential explanatory variables using binary logistic regression. The first model indicated that Soil Type and an Anoxic Environment had influenced the presence of infiltrations (Appendix 1, page 635). Sex was removed and the regression model was run again. In this second model Soil Type, Charnel Deposit and one outcome within Age Range had influenced the presence of infiltrations (Table 5.32; Appendix 1, page 637). The regression model was run again with these three variables. All variables maintained their influence within this third model (Table 5.33; Appendix 1, page 638). The Nagelkerke R-Squared value indicated that this regression model accounted for 30.1% of variation in the occurrence of infiltrations.

Variable	Outcome	Number of Samples	B	Wald	Significance (p-value)
Anoxia	Absent/Present	266	0.573	1.034	0.309
Phase	Later Prehistoric/Historical	266	0.241	0.191	0.662
Soil Type	Overall	266	-	21.167	**0.000***
	Clay	*124*	*4.924*	*7.502*	***0.006***
	Gravel	*65*	*5.243*	*8.270*	***0.004***
	Sand	*24*	*2.998*	*2.684*	*0.101*
	Silt	*35*	*1.945*	*1.521*	*0.217*
	Open	*18*	*0*	-	-
Cave	Non-Cave/Cave	266	-1.974	1.955	0.162
Black Death	Non Black Death/Black Death	266	-0.025	0.002	0.964
State	Articulated/Disarticulated	266	0.289	0.192	0.662
Charnel	Non-Charnel/Charnel	266	1.432	7.866	**0.005**
Age Range	Overall	266	-	6.232	0.101
	Neonate	*29*	*-1.324*	*4.757*	***0.029***
	Child	*20*	*-0.032*	*0.003*	*0.955*
	Juvenile	*24*	*0.549*	*1.082*	*0.298*
	Adult	*193*	*0*	-	-

Table 5.32: Summary of the Parameter Estimates for the second binary logistic regression model of the occurrence of infiltrations.

Variable	Outcome	Number of Samples	B	Wald	Significance (p-value)
Soil Type	Overall	266	-	36.247	**0.000***
	Clay	*124*	*2.945*	*7.535*	***0.006***
	Gravel	*65*	*3.333*	*9.802*	***0.002***
	Sand	*24*	*1.082*	*0.850*	*0.357*
	Silt	*35*	*0.382*	*0.102*	*0.750*
	Open	*18*	*0*	-	-
Charnel	Non-Charnel/Charnel	266	1.537	11.530	**0.001**
Age Range	Overall	266		6.639	0.084
	Neonate	*29*	*-1.256*	*5.171*	***0.023***
	Child	*20*	*0.042*	*0.006*	*0.937*
	Juvenile	*24*	*0.524*	*1.020*	*0.312*
	Adult	*193*	*0*	-	-

Table 5.33: Summary of the Parameter Estimates from the third binary logistic regression model of the occurrence of infiltrations.

Only Soil Type had a significant influence on infiltrations when the results were considered within the Holm-Bonferroni method, although the effect of Charnel Deposits was close to the significance threshold (Appendix 2)**.** The significant influence of Soil Type was maintained when it was placed in a regression model by itself (n=266, B=-0.433, Wald X^2=13.537, p=0.000; Appendix 1, page 639). Bones from clays and gravels demonstrated higher rates of infiltrations (Figure 5.45). Rates of infiltrations amongst sand, silt and open environments were low.

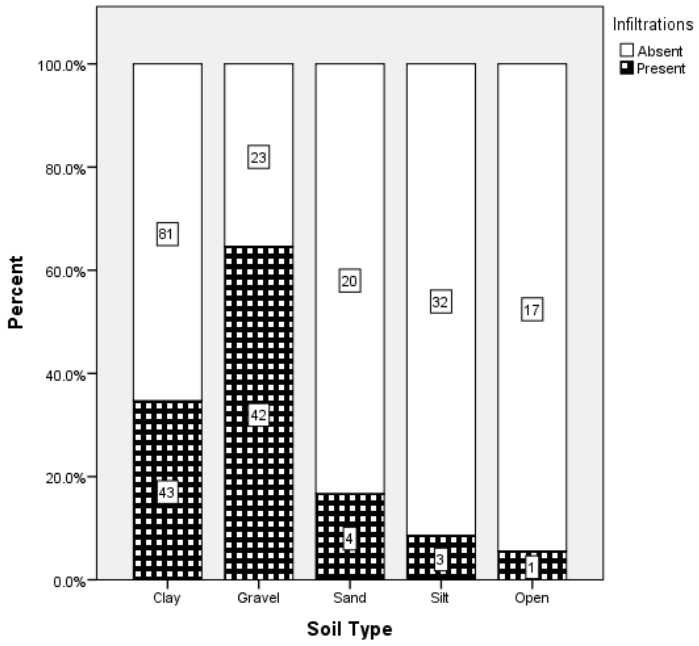

Figure 5.45: Proportional bar chart demonstrating the occurrence of infiltrations within bones recovered from different types of soil. Numbers on bars represent counts of cases.

Site-specific influences may have also contributed to the occurrence of infiltrations. Distributions of infiltrations amongst site assemblages were tested whilst controlling for Soil Type and the influence of charnel samples. Significant differences in the presence of infiltrations were detected between different site assemblages that included clay burial soils, but not between site assemblages from all other burial contexts (Table 5.34). The test of difference between remains from different gravel contexts produced a p-value of less than 0.05. However, the Holm-Bonferroni method suggested that this result could not be accepted as significant (Appendix 2).

There was no obvious patterning of infiltrations amongst the remains from clay sites. Most of the variation was concentrated within bones from Neat's Court and Frälsegården, where infiltrations were particularly abundant (Figure 5.46). Infiltrations were low-occurring within samples from Bolsover and Bradly Fen. These results suggested the occurrence of infiltrations was secondarily controlled by site-specific factors when samples had been buried within contexts that encouraged their formation.

Burial Soil	No. of Samples	Fisher's Exact Test	Significance (p-value)
Clay	71	26.106	**0.000***
Gravel	65	11.638	**0.004**
Sand	24	7.197	0.082
Silt	35	3.819	0.376

Table 5.34: Results of statistical tests of occurrences of infiltrations between bones from different sites whilst controlling for soil type.

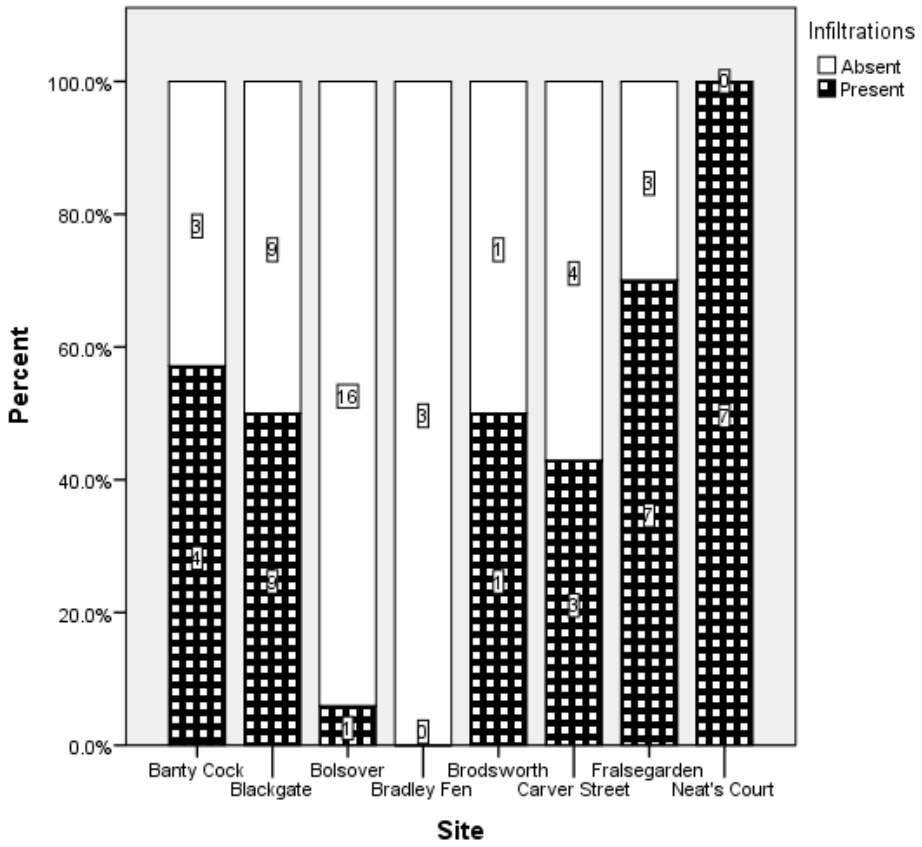

Figure 5.46: Proportional bar chart demonstrating the distribution of infiltrations amongst separate site assemblages recovered from clay environments. Numbers on bars represent counts of cases.

5.4 SUMMARY OF THE KEY FINDINGS FROM THE PRIMARY ANALYSIS

A summary of the key findings of the Primary Analysis ordered by diagenetic parameter is provided below.

Whole OHI

1. The ubiquity of non-Wedl MFD within the samples used in this study meant that Whole OHI score could be taken to represent the extent of bacterial tunnelling.
2. Neonatal bones demonstrated significantly higher Whole OHI scores compared to post-neonatal bones.
3. Bones from anoxic environments demonstrated significantly higher Whole OHI scores compared to bones from aerobic sediments.
4. Bones from Black Death cemeteries demonstrated significantly higher and more variable Whole OHI scores than remains from all other types of sites when the neonatal and anoxic-deposited remains were excluded.

5. Whole OHI scores of Later Prehistoric bones were significantly higher and more variable than those of Historical bones when the neonatal, anoxic-deposited and Black Death remains were excluded.
6. The distribution of Whole OHI scores amongst the Historical samples was significantly leptokurtic and centred on scores of zero after the neonatal, anoxic-deposited and Black Death bones were excluded.
7. There was no significant difference in the distributions of Whole OHI scores between bones from different Historical sites when the neonatal, anoxic deposited and Black Death remains were excluded.
8. Variation in Whole OHI scores amongst Later Prehistoric bones was not explained by specific Later Prehistoric phase or state of articulation when the neonatal, anoxic-deposited and Black Death remains were excluded.

Presence of Bacterial Tunnelling

9. Significantly higher proportions of neonatal samples were free from bacterial tunnelling when compared to the post-neonatal bones. The high proportions of unbioeroded neonatal samples were responsible for their higher overall Whole OHI scores.
10. When the neonatal remains were removed from the distribution, Later Prehistoric samples were significantly more likely to have remained free from bacterial bioerosion than Historical samples.
11. When the effects of phase and neonatal bones were disregarded, bone samples from anoxic environments were significantly more likely to have remained free from bacterial attack.
12. There were no significant differences in the occurrence of bacterial attack within samples from different Historical site assemblages when neonatal and anoxic-deposited bones were excluded.
13. Bronze Age samples were more likely to have remained free from bacterial tunnelling than samples from all other Later Prehistoric periods.

Wedl Tunnelling.

14. Bones that had been deposited in caves demonstrated significantly higher instances of Wedl tunnelling than those that had been buried.
15. Remaining variation in the presence Wedl tunnelling was site-specific and concentrated within remains from Later Prehistoric assemblages.

Persistence of the Periosteal Cortex

16. The periosteal cortex persisted within the majority of samples, regardless of overall histological preservation.
17. The survival of the periosteal cortex was linked to burial sediment. The periosteal surface had been lost most often within remains from silt environments.

Visual Diagenetic Changes

18. Measures of orange staining, inclusions and infiltrations were highly positively correlated with one another.
19. Orange staining and inclusions were present within most bones that had been sampled.
20. The extent of orange-coloured changes to the bone microstructure did not correlate with bacterial bioerosion or the presence of anoxic conditions.
21. All orange-coloured visual changes to the bone microstructures were associated with burial sediment to some degree.
22. All other types of visual diagenetic changes occurred only rarely. These features were linked to the burial environment or site-specific taphonomic processes.

6 RESULTS – SPECIFIC ANALYSIS OF DISCRETE ASSEMBLAGES

This second Results chapter describes the variation in measures of diagenesis within site assemblages. The Primary Analysis had established that site-specific influences were responsible for some of the variation in particular diagenetic parameters. The analysis of diagenesis within site assemblages aimed to establish whether the trends observed within the entire study sample persisted on a smaller controlled scale and determine which variables specific to particular sites may have affected measures of diagenesis. The results from this section would also be used in site-specific interpretations of patterns of bone diagenesis.

This chapter also includes comparisons of bacterial bioerosion within bones from different Later Prehistoric Specific Phases to establish whether characteristic patterns of bacterial attack could be associated with particular Later Prehistoric time periods. Sample sizes from Later Prehistoric sites were small. Analysis of results from Later Prehistoric bones grouped by Specific Phase would provide larger numbers of samples to investigate period-specific variation in diagenetic features. The final section provides the results from the supplementary remains: the Havnø shell midden assemblage and the mummified bone samples from Derrycashel and the Yemen. These samples could not be used in the overall analyses, but their results addressed some of the research aims.

6.1 SITE-SPECIFIC RESULTS

This section will describe the variability in diagenesis within bones from single sites. The Primary Analysis had established that measures of bone degradation and visual diagenetic change did not interact with one another and were influenced by different factors. These precise analyses should help to determine how certain diagenetic changes to bone can be used to infer aspects of funerary treatment or environmental change. Site-specific examinations of results were split between measures of bone degradation and visual diagenetic parameters. Statistical tests were not employed in the analysis of the data from site assemblages. The use of further tests would have exhausted the usefulness of the data, particularly with regards to the problem of multiplicity. Statistical testing was redundant within assemblages that included a small number of sample. Site-specific diagenetic patterns were explored through

examination of visual representations of trends as well as qualitative descriptions and comparisons.

6.1.1 Variation in Diagenetic Parameters within Historical Assemblages

The majority of the variation in bacterial bone bioerosion within the Historical assemblage was explained within the Primary Analysis. The objective of the site-specific analysis of diagenetic parameters within the Historical samples was to test whether correlations observed at the assemblage level persisted on a smaller scale. There was some variation in visual diagenetic parameters within the Historical site assemblages, and it was thought that analysis of these diagenetic parameters across sites would help to determine the factors that influenced their abundance. Some Historical assemblages could not be included in the analysis due combinations of low sample sizes, low levels of variation in diagenetic parameters or lack of salient variable site-specific factors.

6.1.1.1 Bantycock Roman Cemetery, Derbyshire, U.K.

The distribution of Whole OHI score across the bones from the Bantycock site was bimodal. Only two of the samples originated from post-neonatal individuals. Both samples demonstrated high levels of bacterial attack. Neonatal bones demonstrated variable Whole OHI scores, but tended to be better preserved than the post-neonatal samples. The only samples that were free from bacterial bioerosion originated from neonatal individuals. One of the neonatal samples that was badly preserved had been taken from the foetal skeleton that was recovered *in situ* within the skeleton of its mother. Two of the neonatal samples that were free from bacterial bioerosion had lost collagen birefringence. Loss of birefringence was sometimes coincident with microstructural staining. In two samples loss of birefringence did not correspond with staining and was indicative of a non-biotic loss of collagen.

The results from the Primary Analysis had suggested that visual diagenetic were influenced by burial environment. It was possible that visual diagenetic change might be influenced by local differences in the burial environment determined by the position of a skeleton within a site. Too few remains were recovered from the Bantycock site for them to be divided up by precise equal areas. However, the bones could be separated crudely based on whether they had been

retrieved from the cemetery or the settlement. There was no discernable spatial variation in the distribution of orange inclusions amongst the Bantycock samples. Bones sampled from the settlement demonstrated higher levels of orange microstructural staining and increased occurrences of infiltrations compared to bones sampled from the cemetery (Figure 6.1). This result provided some suggestion that visual diagenetic features varied with local burial environment.

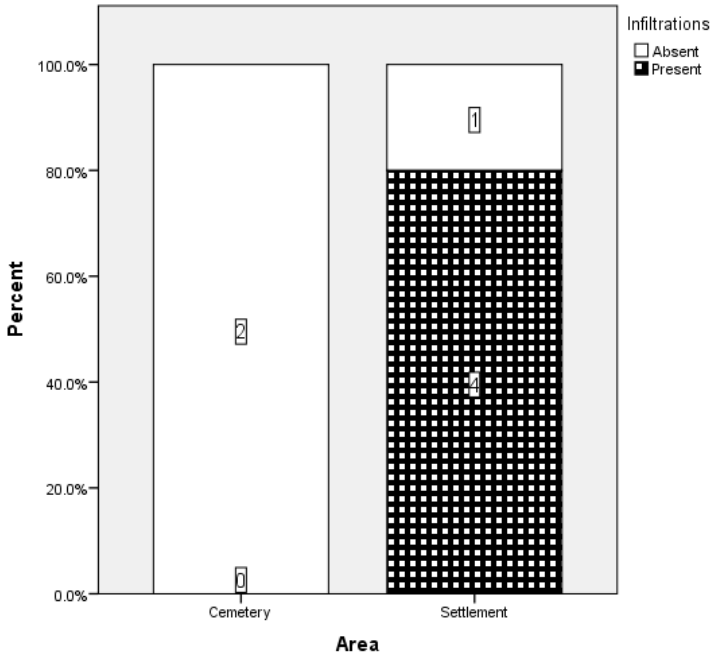

Figure 6.1: Proportional bar chart demonstrating the occurrence of infiltrations within Bantycock samples taken from the Cemetery and Settlement sections of the site.

6.1.1.2 Berinsfield Early Anglo-Saxon Cemetery, Oxfordshire, U.K.

Bacterial bioerosion was invariably high within the samples from the Berinsfield Anglo-Saxon assemblage, but measures of visual diagenetic change were variable. Some skeletons that were sampled had been accompanied by metallic grave goods (Boyle *et al.* 1995). Metallic compounds, particularly ferrous materials, are most often thought to be responsible for discolouration of bone microstructure (Shahack-Gross *et al.* 1997; Hollund *et al.* 2012). Most of the metallic grave goods from Berinsfield were made from iron (Boyle *et al.* 1995). The bone samples from Berinsfield provided an opportunity to investigate whether substances released by grave goods interacted with the bone in a detectable way. The results would help to determine how far measures of visual diagenetic features might contribute to reconstructions of the burial environment. Distributions of orange staining and inclusions were similar

between remains variably found with iron grave goods. Infiltrations appeared more commonly within bones that were not recovered alongside metal goods. The presence of ferrous grave goods within the burial environment had no consistent effect on visual diagenetic changes to the bone microstructure.

It was possible that localised environmental conditions may have affected the extent of visual diagenetic changes to the bone microstructure. Scores of visual features were assessed against the spatial distribution of skeletons across the Berinsfield cemetery. Each skeleton had been allocated a grid reference that corresponded with the areas of the cemetery defined by Boyle *et al.* (1995: 150). The skeletons sampled for this study originated from eight separate grid squares. There were no differences in levels of visual diagenetic parameters between bones from different areas of the site. There was no apparent patterning when samples from adjacent areas were considered together. Variation in visual diagenetic alterations to the Berinsfield samples was not dictated by spatial distribution.

6.1.1.3 Black Gate Anglo-Saxon/Norman Cemetery, Northumberland, U.K.

The Black Gate assemblage yielded neonatal and post-neonatal remains, mixtures of charnel and articulated bone, as well as samples from various different skeletal elements. Neonatal remains from Black Gate demonstrated elevated Whole OHI scores compared to the non-neonatal bones. Bacterial attack was absent from 16% of the Black Gate samples. All of these samples originated from neonatal skeletons.

Three of the Black Gate samples had been taken from humeri, one was from a fibula and a final sample was from a tibia. The majority of these non-femoral samples had come from neonatal material and tended to demonstrate low levels of bacterial bioerosion. All post-neonatal material, regardless of element, demonstrated bacterial tunnelling. Only humeri and femora had been sampled from post-neonatal bones. These skeletal elements demonstrated similar distributions of Whole OHI scores (Figure 6.2). Femora had been allocated a larger range of Whole OHI scores, although this skeletal element were more abundant amongst the site assemblage.

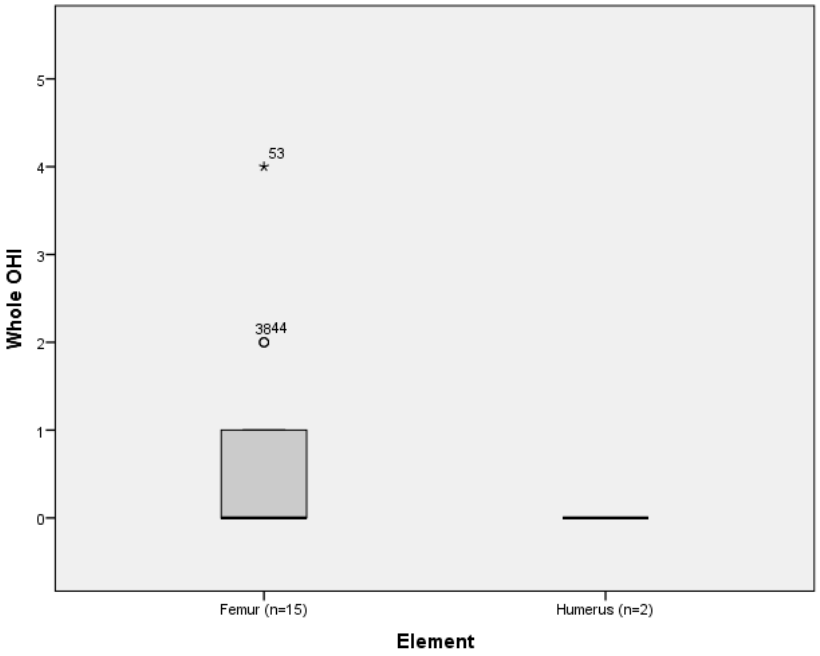

Figure 6.2: Distribution of Whole OHI scores amongst Black Gate post-neonatal samples that had been taken from different skeletal elements.

There was little variation in Whole OHI score amongst the post-neonatal Black Gate remains. A single post-neonatal sample that demonstrated a higher level of histological preservation (Whole OHI=4) originated from the charnel assemblage. However, there was no evidence from the entire study sample or the rest of the Black Gate remains that charnelling was responsible for lower levels of bacterial attack. The spatial distribution of the disarticulated and articulated skeletons sampled from Black Gate was not known and the effect of this factor on visual diagenetic parameters could not be assessed. The Primary Analysis had identified that orange staining, inclusions and infiltrations appeared more often within non-charnel than charnel remains. This patterning persisted to some extent within the non-charnel and charnel remains from Black Gate (Figure 6.3 & Figure 6.4). Variation in orange staining amongst the charnel and non-charnel Black Gate remains was similar, although the median score of the charnel samples was lower. There was no difference in the distributions of orange inclusions between the charnel and non-charnel samples. Infiltrations appeared less often within samples of charnel bone.

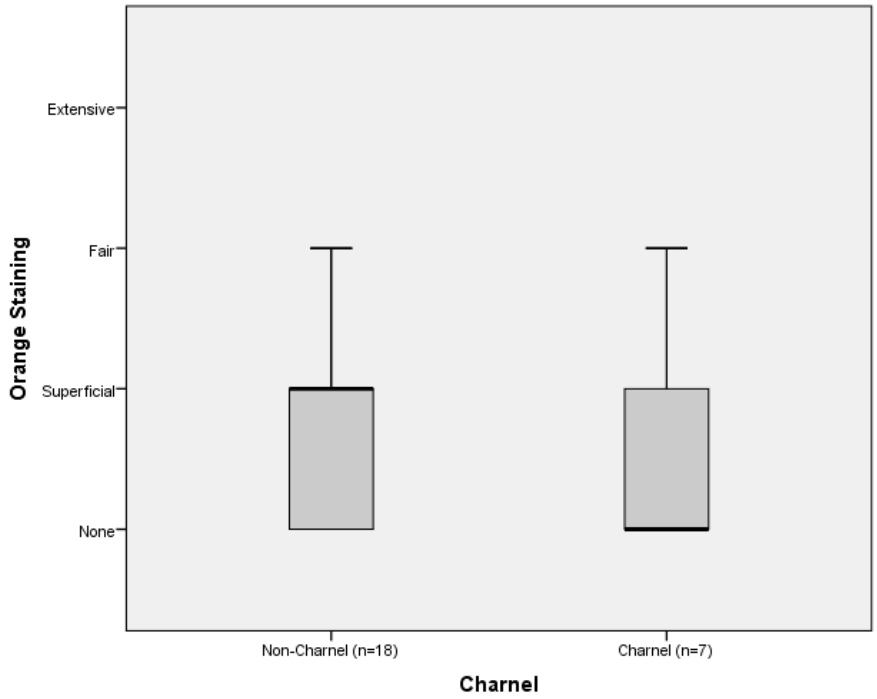

Figure 6.3: Distributions of orange staining amongst samples of charnel and non-charnel bones from Black Gate.

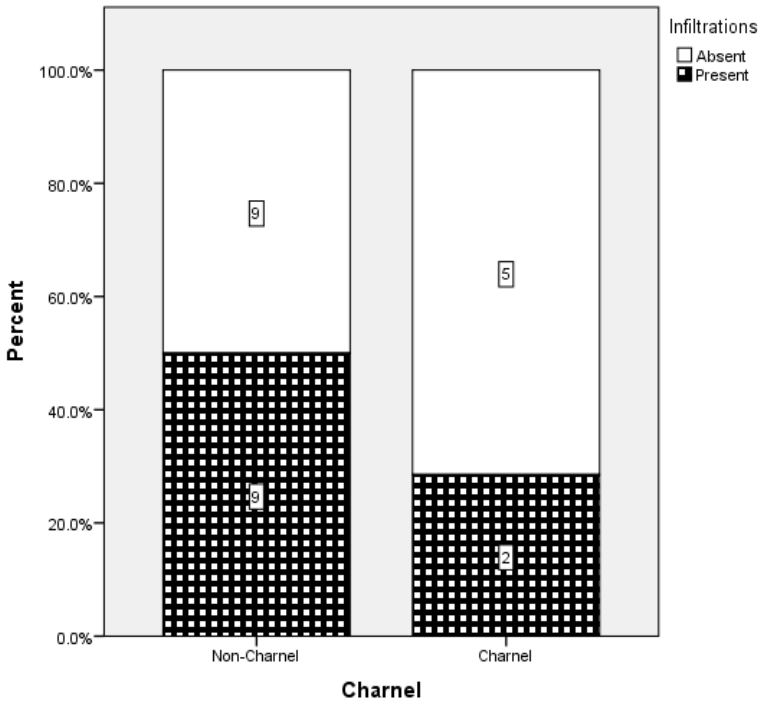

Figure 6.4: Occurrence of infiltrations amongst samples of charnel and non-charnel bones from Black Gate.

6.1.1.4 Carver Street Methodist Chapel Post-Medieval Cemetery, South Yorkshire, U.K.

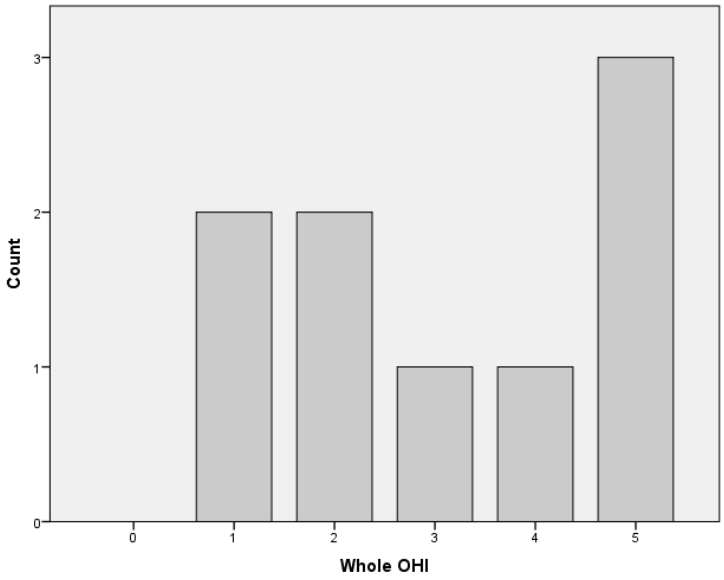

Figure 6.5: Frequency histogram of the distribution of Whole OHI scores amongst the remains from the Carver Street post-medieval cemetery.

The remains from Carver Street had been recovered from waterlogged anoxic sediment. The distribution of Whole OHI scores amongst this assemblage differed markedly from the Historical baseline model. High proportions of samples demonstrated medium and high Whole OHI scores (Figure 6.5). Whole OHI score of five, which appeared rarely amongst the Historical baseline assemblage, was the modal value within the Carver Street assemblage.

Levels of bacterial bioerosion across bones from different parts of the site were investigated to determine whether there was any spatial patterning that could be used to refine explanations of the diversity in bacterial attack. All of the bones that were retrieved from Row 6 within the Carver Street cemetery were free from bacterial bioerosion, whereas bones recovered from outside of this row had all been tunnelled by bacteria (Figure 6.6). The distribution of Whole OHI scores amongst the remains that were not recovered from Row 6 was still elevated compared to the majority of Historical samples taken as a whole. The numbering of the rows reflected the true position of the bodies relative to one another. Remains from Rows 4, 5 and 6 taken together demonstrated an elevated distribution of Whole OHI scores compared to samples from all other rows. These observations suggested that bacterial bioerosion within the Carver Street bones was partly controlled by the position of a skeleton within the cemetery.

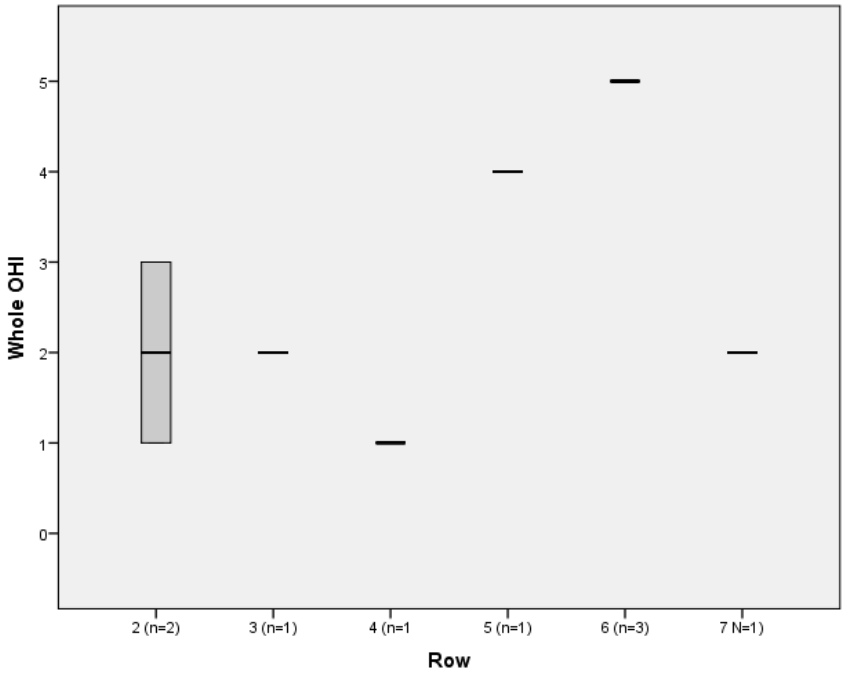

Figure 6.6: Distribution of Whole OHI scores amongst samples of skeletons recovered from different rows within the Carver Street cemetery.

Two of the three bones from Carver Street that were free from bacterial bioerosion demonstrated a loss or obliteration of collagen birefringence. Both of these bones had been retrieved from Row 6. The loss of collagen birefringence did not correspond with areas of orange staining, which suggested that bone protein had been lost via a non-biological mechanism.

Measures of bacterial bioerosion were compared against the extent of orange visual diagenetic parameters to examine their correlation within bones from an anoxic environment. This relationship had been refuted by the results from the whole assemblage, but it was pertinent to investigate any association within bones recovered from sites that were known to have been episodically anoxic. Frequencies of orange inclusions were relatively invariable across the Carver Street assemblage. Distributions of Whole OHI scores were similar amongst bones that had been variably stained orange. The single sample that demonstrated extensive orange staining was free from bacterial bioerosion. Samples that included infiltrations tended to be histologically better preserved than those where infiltrations were absent (Figure 6.7). These results suggested there was a slight positive relationship between certain orange visual diagenetic changes and histological preservation within the Carver Street samples. There was no obvious spatial distribution of visual diagenetic changes amongst the remains from Carver Street. The only bone that demonstrated extensive levels of orange staining originated from Row 6, but staining within remains from this row as a whole was variable.

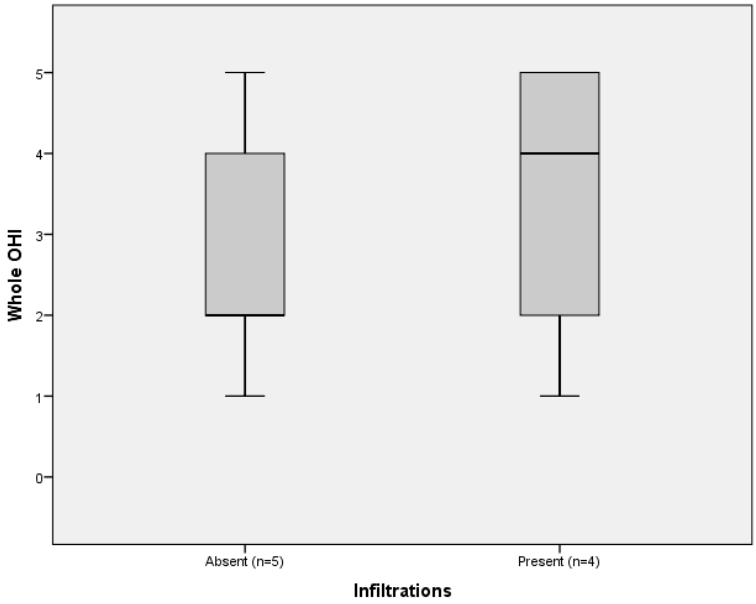

Figure 6.7: Distributions of Whole OHI scores amongst Carver Street samples that variable demonstrated infiltrations.

6.1.1.5 Royal Mint Medieval Cemetery, London, U.K.

The Royal Mint was the only site that included remains that had been recovered from Black Death graves. The distribution of Whole OHI scores amongst the Royal Mint samples differed from what was observed within remains from most Historical sites (Figure 6.8). The majority of Royal Mint samples had been extensively tunnelled by bacteria. However, a substantial proportion of samples demonstrated medium Whole OHI scores, whilst a minor proportion retained excellent histological preservation.

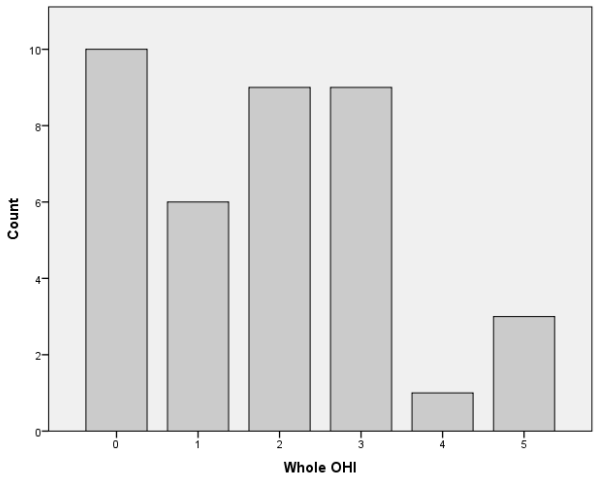

Figure 6.8: Frequency histogram of the distribution of Whole OHI scores amongst remains recovered from the Royal Mint medieval cemetery.

The assemblage from the Royal Mint could be divided by phase into those remains that were likely to have been composed of Black Death victims and those remains that had been interred within the Abbey Church area after the Plague epidemic had subsided. It had already been established within the Primary Analysis that the distribution of Whole OHI scores amongst the Black Death samples differed significantly from the rest of the Historical sample assemblage. Most of the remains that had been allocated the medium and high Whole OHI scores originated from the Black Death cemetery (Figure 6.9). The Whole OHI scores of the remains from the Abbey Church were consistent with the Historical baseline distribution.

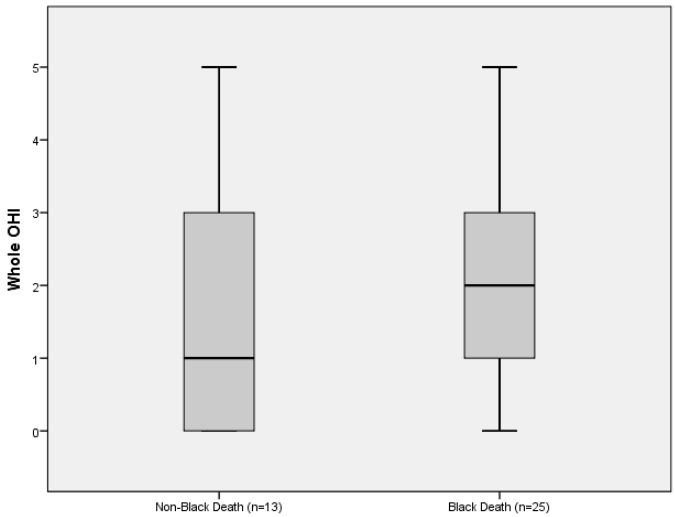

Figure 6.9: Distribution of Whole OHI scores within Royal Mint samples from skeletons that were variably recovered from the Black Death cemetery.

One of specimens from the Abbey Church was anomalously free from bacterial bioerosion. The sample originated from the skeleton that had been surrounded by quicklime within a coffin. This sample was the only one from the site and one of the few from the whole study sample that demonstrated reduced levels of collagen birefringence despite remaining histologically well-preserved. This observation suggested that the unique depositional circumstances of this skeleton had promoted a non-biotic loss of collagen. The rest of the church samples had been bioeroded by bacteria and demonstrated a maximum Whole OHI score of three.

Some of the skeletons from the Royal Mint that were associated with coffin furniture. Distributions of Whole OHI scores were similar amongst samples of skeletons that had been variably deposited within coffins. Skeletons from the Royal Mint had been variably recovered from single and mass graves. There was no difference in Whole OHI scores between samples of bone recovered from these different grave types. Wedl tunnelling was found to be more

prevalent amongst the Royal Mint assemblage compared against the other Historical assemblages. Wedl tunnelling was more common amongst the remains that had been recovered from the Abbey Church rather than the Black Death areas (Figure 6.10). This result suggested that a factor relating to the treatment of the individuals from the church had increased rates of Wedl MFD.

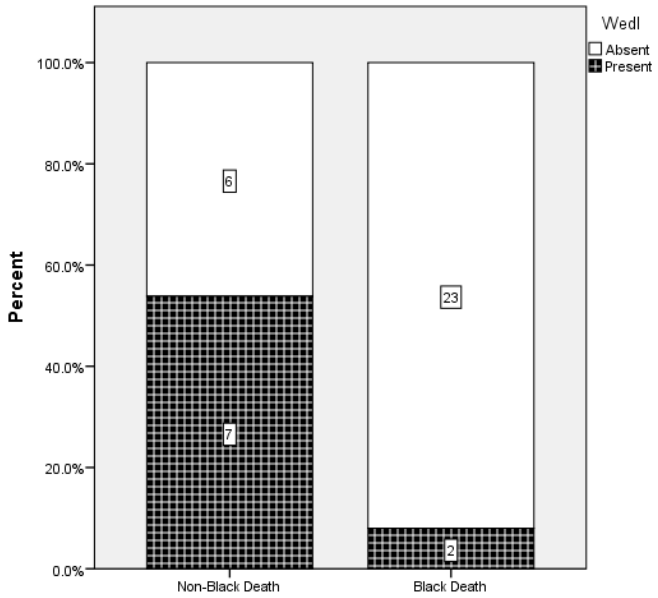

Figure 6.10: Proportional bar chart displaying the occurrence of Wedl tunnelling within Royal Mint samples from skeletons variably recovered from Black Death areas.

Spatial variation in visual diagenetic parameters were investigated amongst the Royal Mint sample set. Spatial variation was determined by whether a skeleton originated from the eastern cemetery, the western cemetery, or the abbey church. There were slight differences in levels of orange microstructural staining between remains from different parts of the site. Bones from the eastern cemetery tended to demonstrate higher levels of microstructural staining, although there was substantial overlap between the three distributions (Figure 6.11). The spatial distributions of orange inclusions and infiltrations echoed the results from the orange staining. The similar variability of these features suggested that the burial sediment in different parts of the Royal Mint cemetery had influenced frequencies of visual diagenetic changes to bone microstructures.

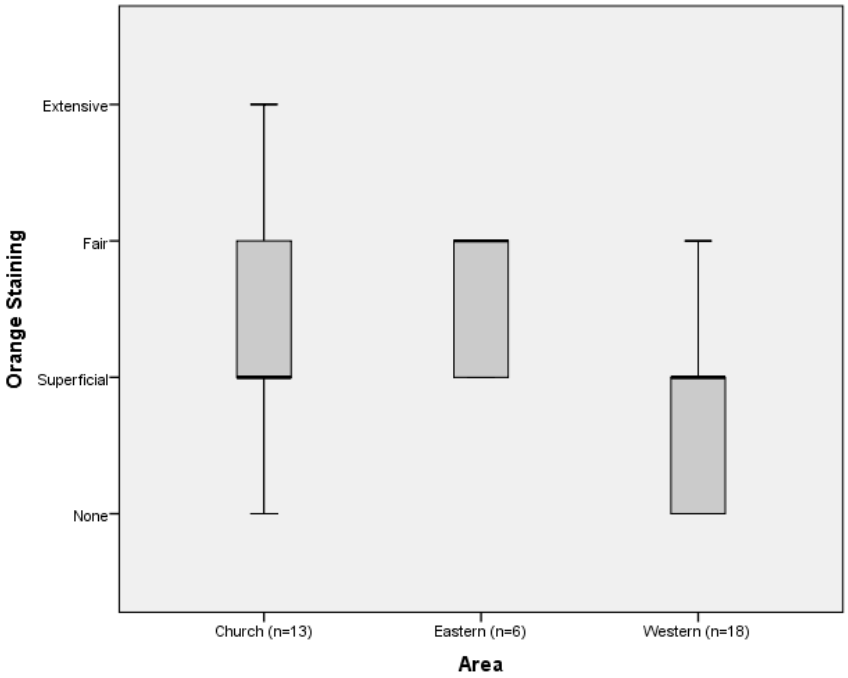

Figure 6.11: Distributions of orange staining amongst Royal Mint samples from skeletons recovered from different areas of the site.

6.1.1.6 St. Hilda's Medieval/Post-Medieval Cemetery, Northumberland, U.K.

The Coronation Street assemblage included three samples from neonatal skeletons. These samples demonstrated an elevated distribution of Whole OHI scores compared to the post-neonatal specimens (Figure 6.12). The neonatal bones were more likely to have remained free from bacterial bioerosion.

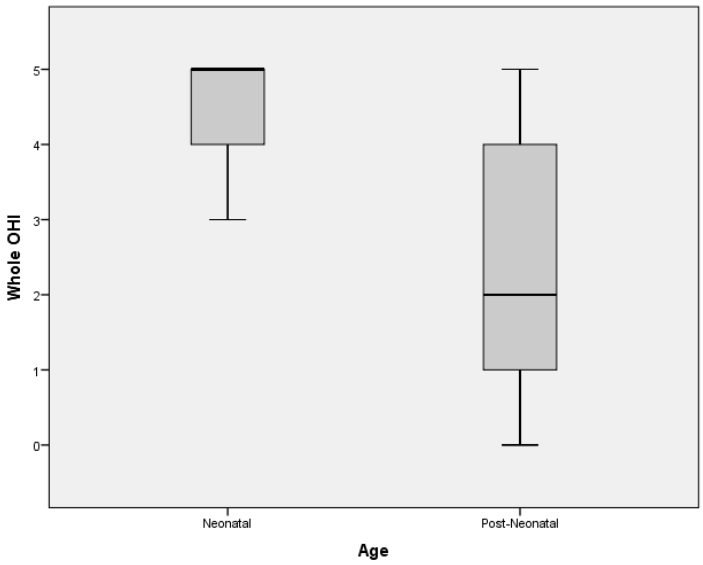

Figure 6.12: Box-and-whisker plot of the distributions of Whole OHI scores amongst neonatal and post-neonatal remains from the Coronation Street medieval/post-medieval cemetery.

It was likely that skeletons from Coronation Street had been deposited within anoxic sediment. Whole OHI scores of the Coronation Street post-neonatal samples were variable and differed markedly from the rest of the Historical remains. Whilst there was a peak within the lowest Whole OHI scores, there were also equal representations of medium and high scores (Figure 6.13). The distribution of Whole OHI scores amongst this assemblage was similar to what was observed within the waterlogged Carver Street samples. The main difference between the two sites was the higher numbers of remains from Coronation Street that scored low Whole OHI values.

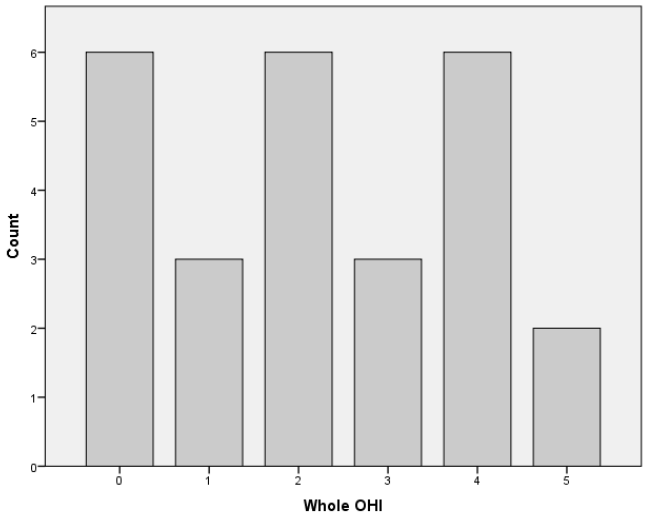

Figure 6.13: Frequencies of Whole OHI scores amongst the samples from Coronation Street (the neonatal samples were excluded).

The precise provenances of the remains that constituted the Coronation Street assemblage were not known. Spatial distribution of bacterial bioerosion and visual diagenetic changes within this site assemblage could not be examined. The retrieval of the Coronation Street remains from an anoxic environment meant that it was possible that there would be a relationship between measures of bacterial bioerosion and visual diagenesis (Hollund *et al.* 2012). Distributions of Whole OHI scores were not affected by differences in levels of orange staining. All bone samples that did not include orange inclusions demonstrated Whole OHI scores of zero. Histological preservation was higher amongst remains that demonstrated orange inclusions, although variations in the abundance of inclusions had no subsequent effect on Whole OHI score. Bones that were free from infiltrations tended to demonstrate higher Whole OHI scores, but this difference was very slight. These patterns did not amount to notable trends in relationships between bacterial bone bioerosion and visual changes to the bone microstructure.

6.1.1.7 St. Leonard's Hospital Medieval Cemetery, Lincolnshire, U.K.

All of the bones from the cemetery of St. Leonard's hospital had been extensively bioeroded by bacteria. Some of the skeletons that had been sampled from this site had demonstrated lesions consistent with leprosy. The presence of leprotic lesions on skeletons had not affected levels of bacterial bioerosion in related bone samples. The intensity of orange visual diagenetic parameters was compared between bones from the east and west areas of the Grantham site. Measures of orange staining and inclusions were similar amongst remains from different parts of the cemetery. The single sample that included infiltrations originated from the western area, but this result did not amount to a notable spatial trend in visual diagenesis.

6.1.1.8 St. Mary & Saint Laurence Medieval/Post-Medieval Cemetery, Derbyshire, U.K.

The Bolsover assemblage included neonatal and post-neonatal remains as well as charnel and non-charnel bones. Neonatal bone samples demonstrated an elevated distribution of Whole OHI scores compared with the post-neonatal samples (Figure 6.14). Four out of five of the samples from the site that were free from bacterial bioerosion had been taken from neonatal skeletons. All of the neonatal bone samples that were free from bacterial attack were recovered from the northern wall of the St. Mary and St. Laurence church.

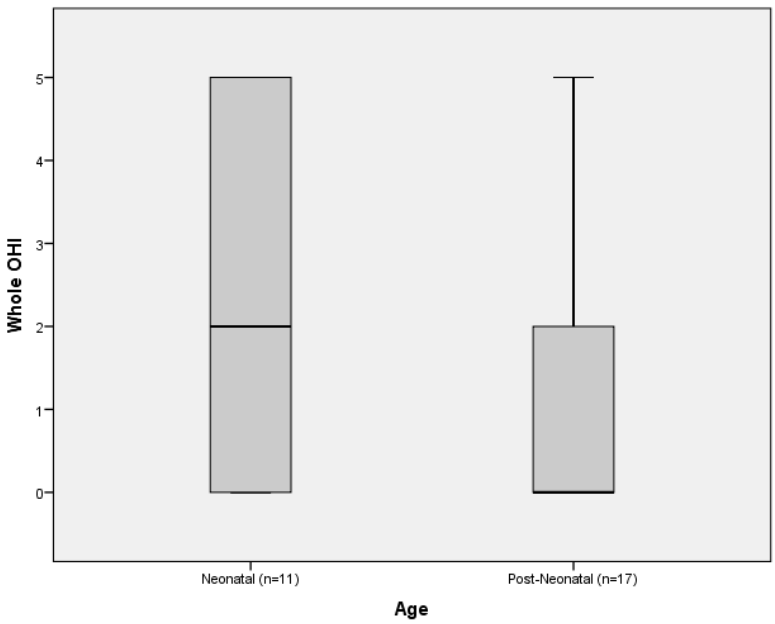

Figure 6.14: Distribution of Whole OHI scores amongst Bolsover samples from neonatal and post-neonatal skeletons.

The only post-neonatal bone that remained free from microbial bioerosion had been taken from the charnel assemblage. Charnel post-neonatal bones demonstrated an elevated distribution and wider range of Whole OHI scores compared to non-charnel samples. However, distributions of charnel and non-charnel Whole OHI scores overlapped and were consistent with patterns of bacterial bioerosion observed amongst the rest of the Historical baseline assemblage (Figure 6.15).

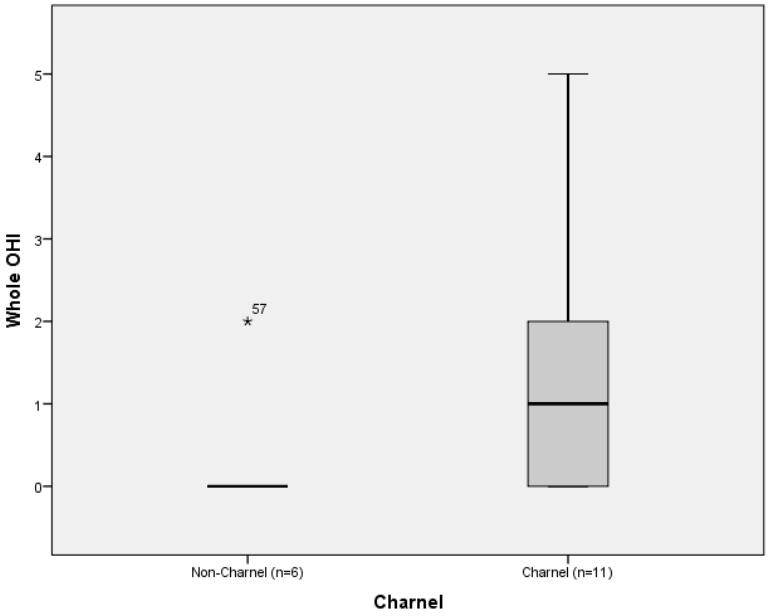

Figure 6.15: Distribution of Whole OHI scores amongst Bolsover samples from articulated and charnel skeletons.

The articulated remains sampled from Bolsover originated from three different areas: the north churchyard, the south churchyard and the church tower. The majority of skeletons sampled (65%) originated from the north side of the church. The provenance of the disarticulated material could not be established. Visual measures of diagenesis were tested between remains from these areas in order to establish whether variation could be attributed to the spatial distribution of skeletons. Yellow staining was only identified within samples of disarticulated material and brown discolouration was present within only one sample of an articulated skeleton. Levels of orange staining and inclusions tended to be higher amongst remains from the north side of the church and the church tower compared with the south side, although there was overlap between these distributions (Figure 6.16 & Figure 6.17). Infiltrations were only found within one sample from the north side of church. Therefore there was some suggestion that visual diagenetic features varied with position of a skeleton within the cemetery.

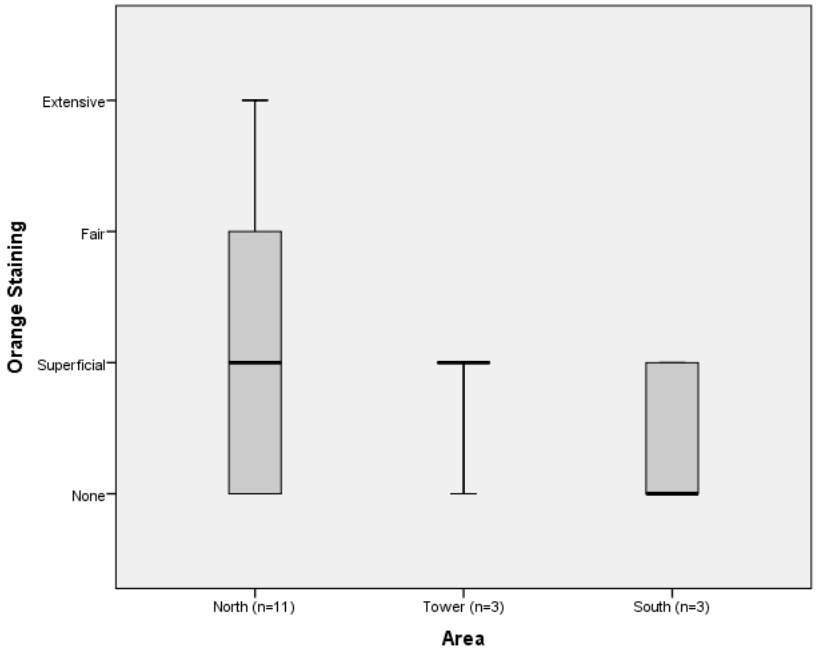

Figure 6.16: Distributions of orange staining amongst Bolsover samples from skeletons that had been recovered from different parts of the site.

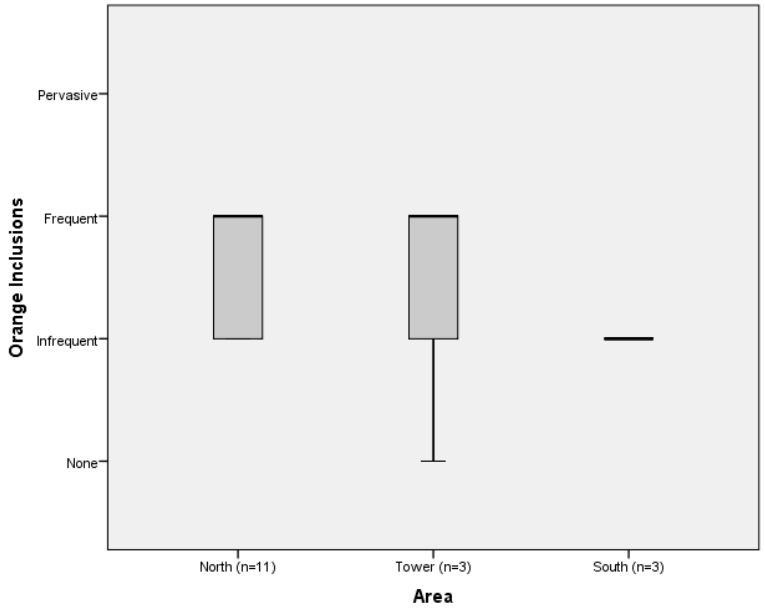

Figure 6.17: Distributions of orange inclusions amongst Bolsover samples from skeletons that had been recovered from different areas of the site.

The Primary Analysis had suggested that levels of orange staining and infiltrations were lower within samples from charnel bones. This finding was supported by the results from the Bolsover assemblage (Figure 6.18 & Figure 6.19).

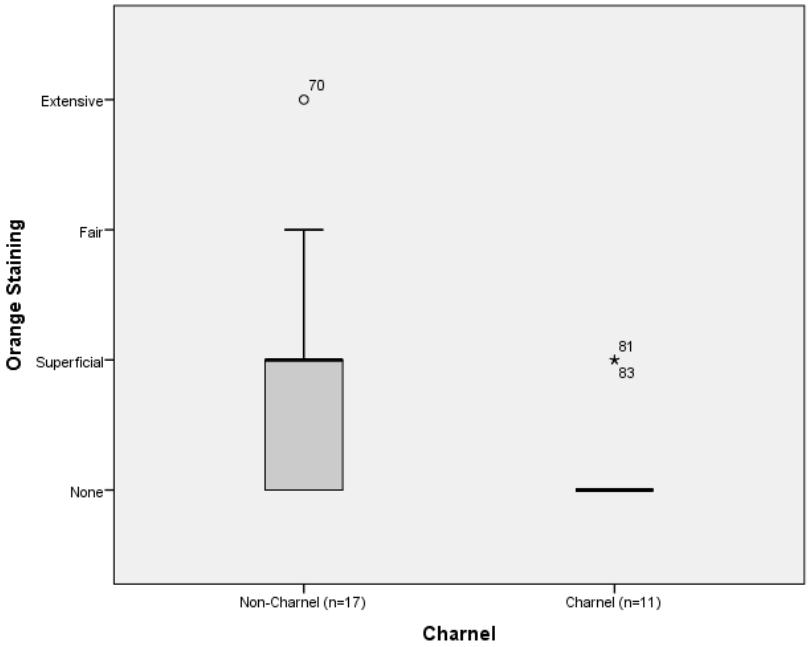

Figure 6.18: Distribution of orange staining amongst samples of charnel and non-charnel remains from Bolsover.

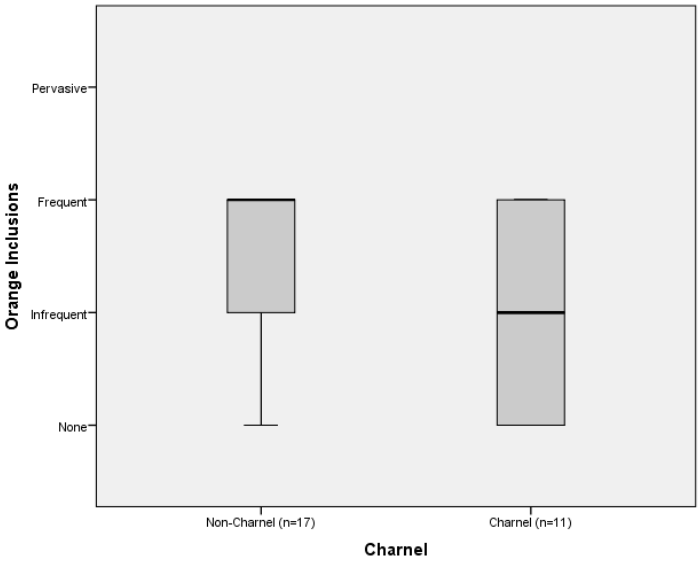

Figure 6.19: Distributions of orange inclusions amongst samples of charnel and non-charnel bones from Bolsover.

6.1.2 Variation in Diagenetic Parameters within Later Prehistoric Assemblages

Most of the variation in histological preservation of bone samples from Later Prehistoric sites was not explained by the factors tested within the Primary Analysis. Confirmation of the hypotheses put forward in the Methodology suggested that this unexplained variation was likely to relate to how remains had been treated in the early *post mortem* period. Histological results from separate Later Prehistoric assemblages were investigated to examine whether

patterns observed at the assemblage level were replicated at discrete sites. The results also provided an analytical base for discussions regarding the possible funerary treatment of remains from each site. Comparison of the diagenetic signatures of each assemblage to the Historical baseline model would help to determine how degradation of bone at each site had deviated from that which is encouraged by immediate burial. Reference to forensic models of decomposition would help to determine what sorts of *post mortem* processes might have been responsible for these deviations. Descriptions of the visual diagenetic changes were included in order to provide an idea of their prevalence and assess the likelihood that specific localised environmental conditions were responsible for variation in bacterial bone bioerosion. Spatial variation in visual diagenetic changes across sites could not be assessed in most cases due to low sample size and spatial variability.

6.1.2.1 Beeston Tor CX Neolithic Cave Deposits, Staffordshire, U.K.

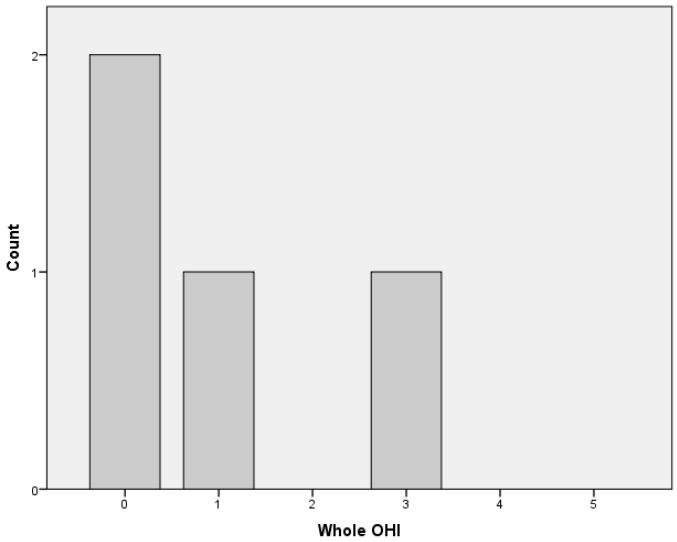

Figure 6.20: Frequency histogram of the distribution of Whole OHI scores amongst the Neolithic remains sampled from the Beeston Tor CX cave assemblage.

Four disarticulated bones were sampled from Beeston Tor CX. All bone samples demonstrated low Whole OHI scores (Figure 6.20). The exception was specimen 145, which was allocated a Whole OHI score of three. This distribution of Whole OHI scores was consistent with the Historical baseline. All samples demonstrated Wedl tunnelling within areas of bone that had not been consumed by bacterial tunnelling. Wedl tunnelling was found rarely amongst the whole study sample. The result from Beeston Tor was consistent with the finding from the

Primary Analysis that Wedl tunnelling occurred more often within bones from caves. Three of the four Beeston Tor samples demonstrated orange staining. This staining was superficial in two cases and fair in one. Infrequent or frequent orange inclusions were detected within all of the samples from this site. Infiltrations were only recorded from one of the Beeston Tor samples.

6.1.2.2 Bradley Fen Late Bronze Age Settlement, Cambridgeshire, U.K.

The three Bradley Fen samples had been taken from articulated skeletons. All of these samples demonstrated very good to excellent levels of histological preservation (Whole OHI=4 or 5). Two of the samples (Sk. 573 & Sk. 785) included minor levels of bacterial bioerosion. The sample from Burial 853 was free from microbial bioerosion. Burial 853 had been recovered from an anoxic environment. When Burial 853 was removed from the distribution, the Whole OHI scores of the Bradley Fen remains were still elevated compared to the Historical baseline.

There was some doubt over whether the decomposition of all of the bodies from Bradley Fen had been affected by intermittent waterlogging. The Whole OHI scores of the Bradley Fen remains lay within the upper range of the distribution for the Historical anoxic-deposited bone samples (Figure 6.21). This result decreased the likelihood that the high level of histological preservation within the remains from Bradley Fen was attributable to waterlogging, although it was possible that the small sample size produced a skewed distribution.

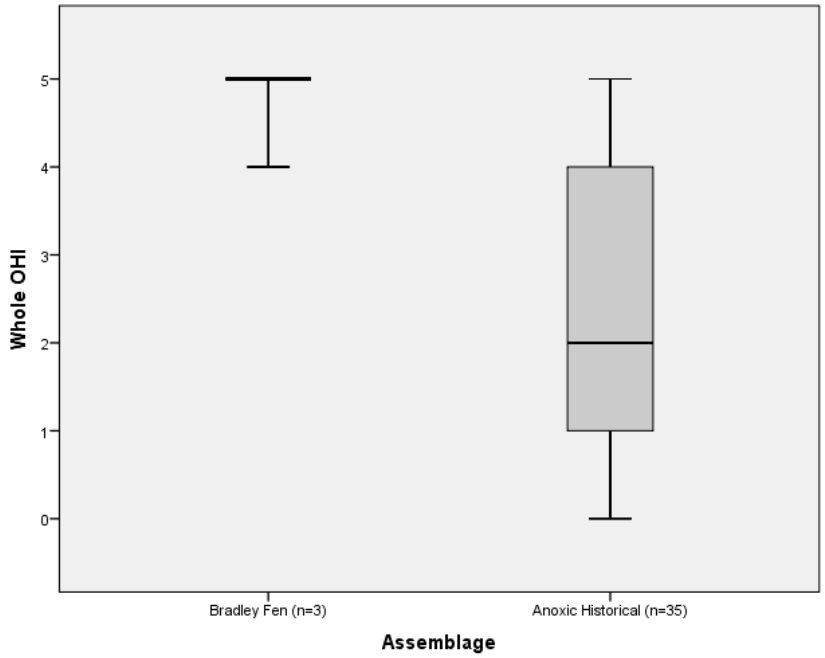

Figure 6.21: Distribution of Whole OHI scores amongst the Bradley Fen samples compared to Historical samples from skeletons recovered from anoxic environments (neonatal samples were excluded).

All of the Bradley Fen thin sections demonstrated orange inclusions. These inclusions were found ubiquitously throughout the natural porosities of Burial 853 but infrequently within the samples taken from Burials 573 and 785. All of the Bradley Fen thin sections demonstrated orange microscopic staining at their periosteal and endosteal margins. This peripheral staining was slight and inconsistent within the thin sections from Burial 853, but much more intense and intrusive within samples from Burials 573 and 785. Orange staining was often observed within areas of microbial destruction. No infiltrations were present within any of the Bradley Fen samples.

6.1.2.3 Bilham Farm Iron Age Enclosure, South Yorkshire, U.K.

The Bilham Farm articulated skeletons had both been extensively bioeroded by bacteria and were allocated Whole OHI scores of zero. Wedl tunnelling was identified in both samples in small areas of bone microstructure that had not been consumed by bacterial attack. The distribution of Whole OHI scores amongst these samples lay within the Whole OHI scores of the baseline Historical population. Neither sample demonstrated significant levels of microstructural staining. Orange inclusions appeared frequently within both samples. Infiltrations were present within the thin section from Sk. 1022.

6.1.2.4 Carsington Pasture Cave Iron Age/Neolithic Cave Deposit, Derbyshire, U.K.

Eighteen disarticulated bones had been sampled from the Carsington Pasture Cave. Histological preservation varied from excellent to poor. A large proportion of samples lay within the middle of this range (Whole OHI=2) (Figure 6.22). Two of the bones originated form neonatal skeletons. Both of these samples were free from bacterial tunnelling. The distribution of Whole OHI scores amongst the post-neonatal remains from Carsington Pasture Cave, was more elevated and variable than the Historical baseline model as defined by the median value and interquartile range (Figure 6.23). Two of the post-neonatal samples were free from bacterial bioerosion. One of these samples was taken from a bone that demonstrated cut marks indicative of dismemberment. The Carsington Pasture Cave bones had been recovered from three different chambers and passageways. Radiocarbon dates had suggested that the assemblages from each of these contexts may have belonged to separate phases of activity. There were no discernable differences in distributions of Whole OHI scores between the samples of bone recovered different parts of the cave. Wedl tunnelling was identified within 67% of the Carsington Pasture Cave thin sections, which represented an unusually high occurrence. This result was consistent with the finding that Wedl tunnels appeared more frequently within bones from caves.

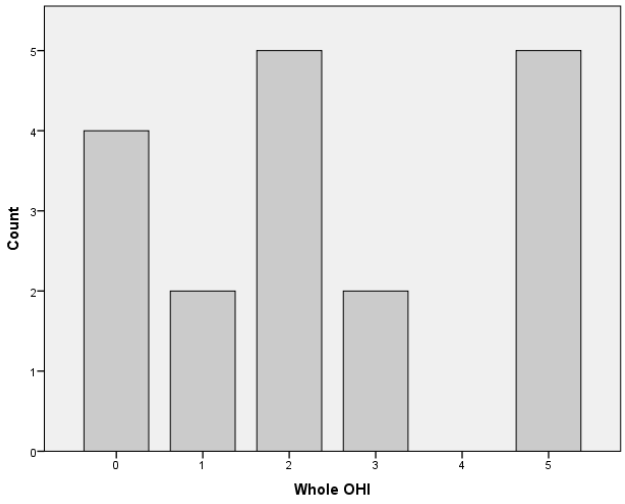

Figure 6.22: Frequency histogram of the distribution of Whole OHI scores within the Neolithic/Iron Age remains recovered from Carsington Pasture Cave.

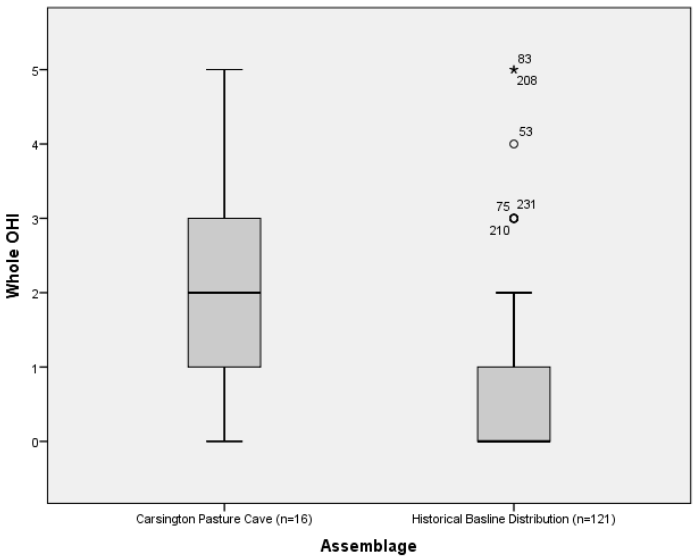

Figure 6.23: Distribution of Whole OHI scores amongst the Carsington Pasture Cave samples compared to the Historical baseline assemblage (neonatal bones were excluded).

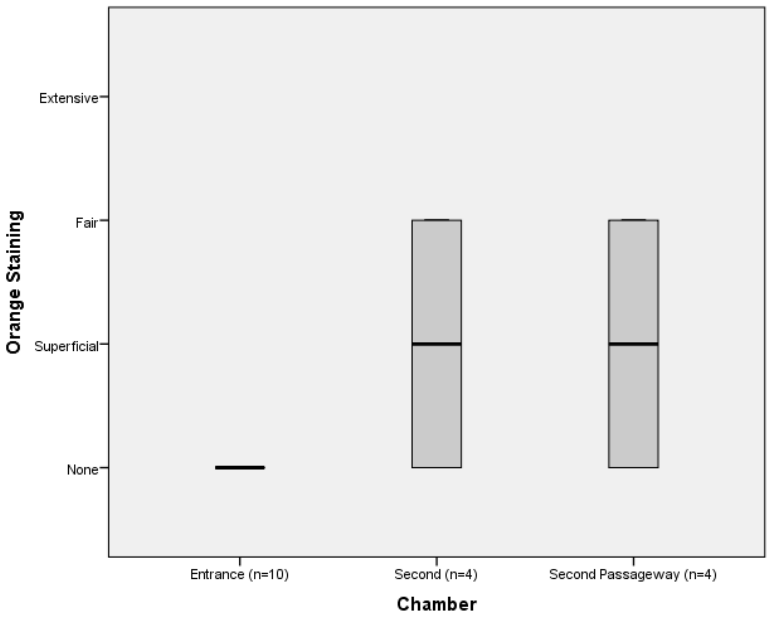

Figure 6.24: Box-and-whisker plot illustrating the distribution of orange staining within the Neolithic/Iron Age remains recovered from different chambers within the Carsington Pasture Cave.

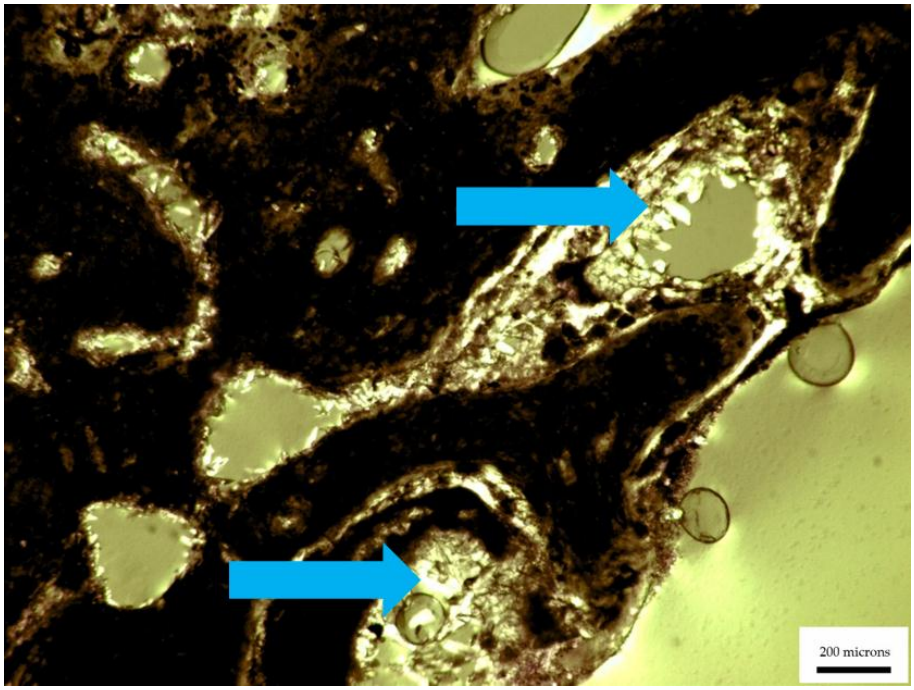

Image 6.1: Micrograph of the endosteal surface of a femoral thin section from specimen CPC-02-FL237 from Carsington Pasture Cave under polarised light. The porosities demonstrate a unique form of crystalline inclusion that appeared transparent under normal light (arrows).

Five of the eighteen samples from Carsington Pasture Cave demonstrated superficial or fair levels of microstructural staining. The staining was orange-coloured in all but one case where it was yellow. The yellow staining was only superficial and may have represented a weaker form of the orange discolouration. Orange staining was absent amongst the remains from the entrance chamber but present in similar quantities within the bones recovered from the second chamber and second passageway (Figure 6.24). Inclusions appeared within fourteen of the eighteen samples. One sample demonstrated types of inclusions that were unique to the bones from this site. These inclusions consisted of transparent crystalline formations that became illuminated under polarised light (Image 6.1). There were no notable trends in the distribution of inclusions amongst bones from different chambers that corresponded with the patterning of orange staining.

6.1.2.5 Cladh Hallan Bronze Age Settlement, South Uist, U.K.

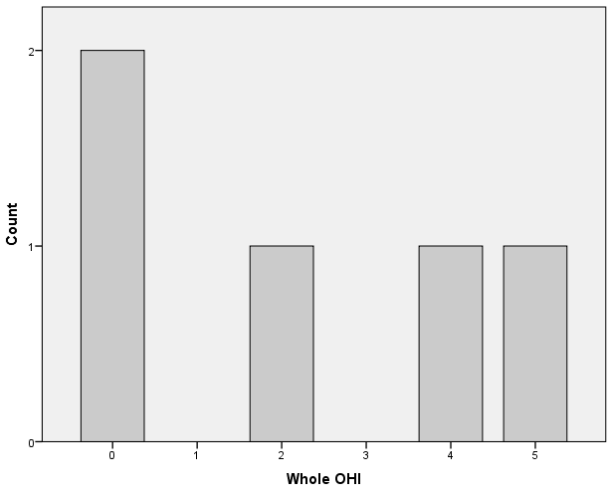

Figure 6.25: Frequency histogram of the distribution of Whole OHI scores across the remains recovered from the Cladh Hallan Bronze Age settlement.

The samples from Cladh Hallan had been taken from a mixture of articulated, partially articulated and disarticulated remains. Whole OHI score across the Cladh Hallan samples were variable. Samples demonstrated the lowest, highest and medium levels of histological preservation (Figure 6.25). The distribution of Whole OHI scores within the Cladh Hallan remains was slightly elevated compared to the Historical baseline model. Variation in Whole OHI score of the Cladh Hallan remains, as defined by the interquartile range, was broader than within the Historical baseline (Figure 6.26). The Cladh Hallan distribution mostly deviated from the Historical baseline in terms of the remains that were allocated Whole OHI scores of four and five. These scores had been allocated to the articulated potentially mummified CH 2638 individual and the disarticulated CH-C femur respectively.

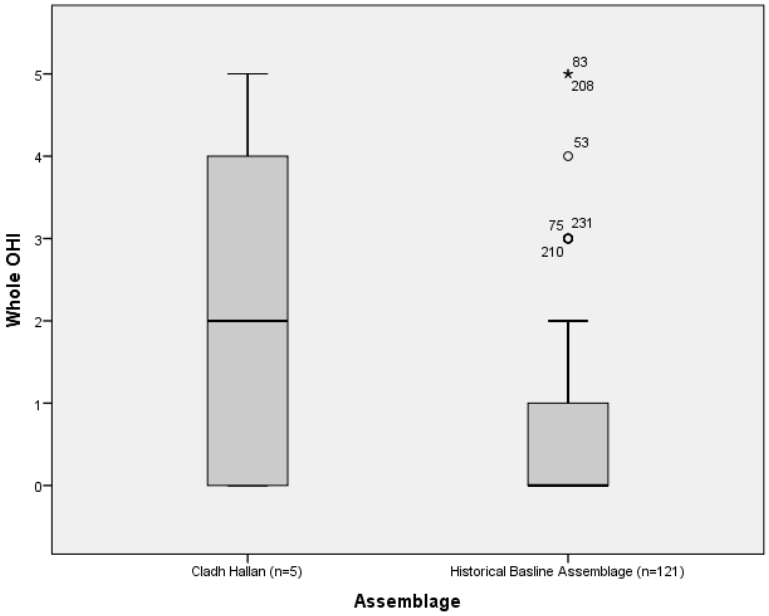

Figure 6.26: Distribution of Whole OHI scores amongst the Cladh Hallan samples and the Historical Baseline Assemblage.

Four out of the five Cladh Hallan samples had been stained. The staining was superficial in three cases and extensive in one. Three of the stained bones demonstrated orange staining and one had been stained yellow. The yellow staining was only superficial and may have represented a weaker form of the orange staining observed in other samples from the site. Infrequent and frequent orange/ inclusions were identified in two samples. Only one sample demonstrated infiltrations.

6.1.2.6 Cnip Headland Bronze Age Cemetery, Isle of Lewis, U.K.

Seven disarticulated, partially articulated and articulated bones from Cnip had been sampled as part of the current study. Only one of the bones samples demonstrated bacterial tunnelling. Bacteria had destroyed the majority of the microstructure within this specimen (Whole OHI=0). The rest of the bones were free from microbial attack. One of the samples had originated from a neonatal skeleton. The dominance of a well-preserved histological signature amongst the Cnip assemblage meant that the preservation of the neonatal individual did not set it apart from most of the post-neonatal remains. All of the well-preserved post-neonatal remains from Cnip represented outliers to the Historical baseline assemblage.

Collagen birefringence was reduced within two of the histologically well-preserved bones from Cnip. Both of these bones also demonstrated brown staining. The areas of bone microstructure where collagen birefringence was reduced corresponded with staining. Superficial brown staining was also identified within two other samples from Cnip, although in these cases staining was not extensive enough to have affected birefringence. The Cnip bones had been retrieved from discrete deposits a few metres apart from one another, named Areas A, C and D. Brown staining of variable intensity was only present within samples from Areas A and C. Orange inclusions appeared frequently or infrequently within all of the bones from Cnip, but infiltrations were always absent. There was no consistent overall patterning in spatial distributions of visual diagenetic features amongst samples.

6.1.2.7 Danebury & Suddern Farm Iron Age Settlements, Hampshire, U.K.

The Suddern Farm and Danebury bones originated from archaeological sites that were temporally and geographically close. It was decided that the results from these sites would be best discussed together. Samples had been taken from disarticulated, partially articulated and articulated remains. The histological preservation of most of the Danebury and Suddern Farm samples was poor. However, Whole OHI score was variable within these lower confines (Figure 6.27). All samples demonstrated bacterial bioerosion. One outlying sample demonstrated only limited levels of bacterial attack (Whole OHI=5).

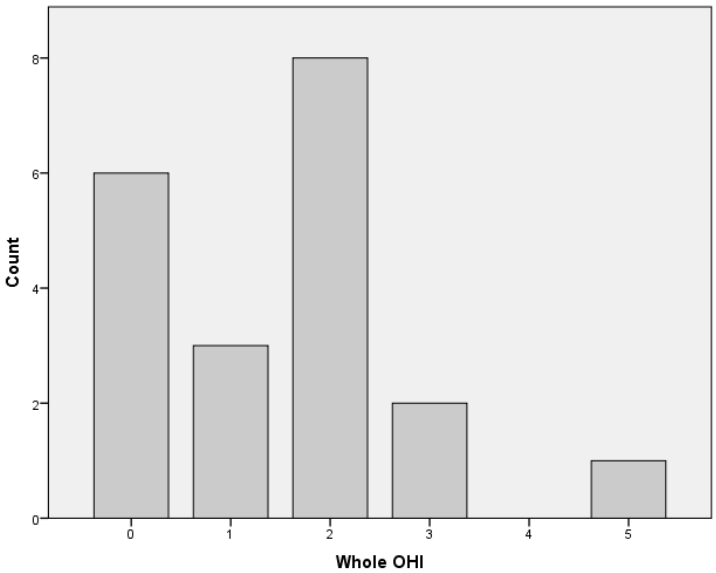

Figure 6.27: Frequency histogram displaying the distribution of Whole OHI scores across remains retrieved from the Iron Age Danebury and Suddern Farm settlements.

The distribution of Whole OHI scores of the Danebury and Suddern Farm samples was elevated and variable when compared with the Historical baseline signature (Figure 6.28). The Danebury & Suddern Farm assemblage included higher proportions of bone samples that had been allocated Whole OHI scores of two, which was the modal value.

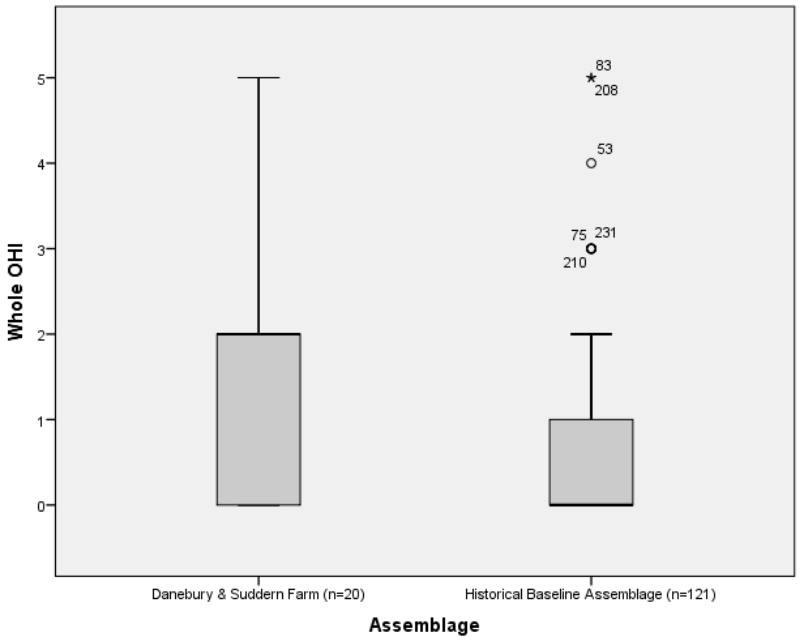

Figure 6.28: Distribution of Whole OHI scores amongst the Danebury & Suddern Farm samples compared against the Historical Baseline Distribution.

Cunliffe & Poole (2000: 168) had suggested that the Danebury and Suddern Farm assemblages represented different funerary traditions practised by the same society and it was therefore pertinent to compare the diagenetic signatures of samples from these two sites. The two Suddern Farm samples demonstrated a slightly elevated distribution of Whole OHI scores compared to the Danebury specimens, although overall these two distributions were consistent with one another.

The various states of skeletal articulation represented within the samples from Danebury & Suddern Farm may have reflected separate forms of treatment. The samples were split into categories of burial type defined within the site report: Disarticulated Elements, Whole Bodies, Incomplete Bodies and Multiple Partially Articulated bones. There were no observable differences in distributions of Whole OHI scores based on these categories. The original groups were simplified into three categories of articulated, partially articulated and disarticulated skeletons. The distributions of Whole OHI scores amongst the articulated and partially

articulated remains were very similar. The histological preservation of the disarticulated bones was consistently very poor, apart from the single anomalous best preserved sample (Deposit 130). The main variation in bacterial bioerosion existed between the articulated/partially articulated remains combined and the disarticulated discrete bones (Figure 6.29).

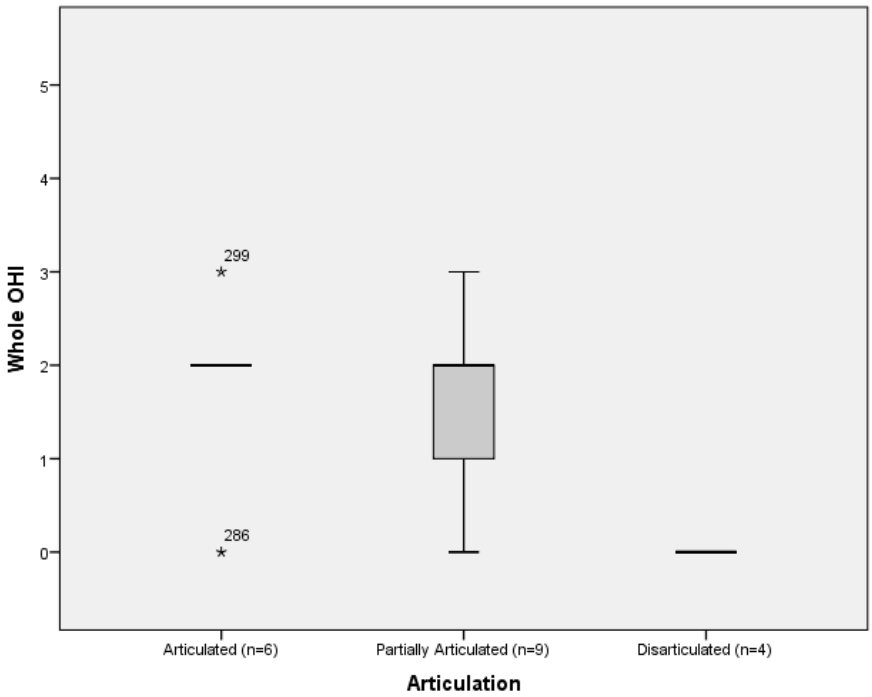

Figure 6.29: Distribution of Whole OHI scores amongst Danebury & Suddern Farm samples from skeletons that demonstrated variable levels of articulation (Deposit 130 was excluded).

The human remains recovered from Danebury were associated with different Ceramic Phases (Cunliffe 1983). These phases had been used to set out the chronology of the site within the Iron Age. The majority of bones sampled originated from Ceramic Phases 6 and 7. Analysis of the changes in burial practice over time had identified specific trends, and it was possible that some of the variation in Whole OHI score amongst the Danebury remains was attributable to the different phasing of depositions (Cunliffe 1984; Cunliffe & Poole 2000). Distribution of Whole OHI scores within bones from Ceramic Phases 3, 6 and 7 were very similar. Histological preservation within bones from Ceramic Phase 8 appeared to be higher than within remains from all other Ceramic Phases, although this patterning was probably a result of low numbers of remains from Ceramic Phase 8 (n=2) combined with the presence of the anomalous Deposit 130.

Bayesian analysis of radiocarbon dates by Buck *et al.* (1992) had suggested that Cunliffe's Ceramic Phases represent continua rather than discrete temporal horizons. Therefore, the

bones were regrouped by Ceramic Phase into Early (Ceramic Phases 1-3), Middle (4-6) and Late periods (7-8). The distribution of Whole OHI scores within samples of bone from the Late period was more variable and elevated than within samples from the Early and Middle periods. However, this patterning was also likely to reflect the influence of Deposit 130, which belonged to the Late period. It was considered whether variation in Whole OHI score across the Danebury samples may have been related to a combination of phase and state of articulation. However, sample sizes were too low to meaningfully compare the Danebury and Suddern Farm assemblages using both variables.

The Danebury and Sudden Farm samples demonstrated elevated rates of Wedl tunnelling compared to most other site assemblages. Wedl tunnels were absent from the samples of disarticulated bone but occurred more frequently within samples from articulated and partially articulated skeletons (Figure 6.30). This patterning was similar to the distribution of bacterial tunnelling. The partially articulated and articulated remains had been subject to processes that increased their susceptibility to Wedl tunnelling.

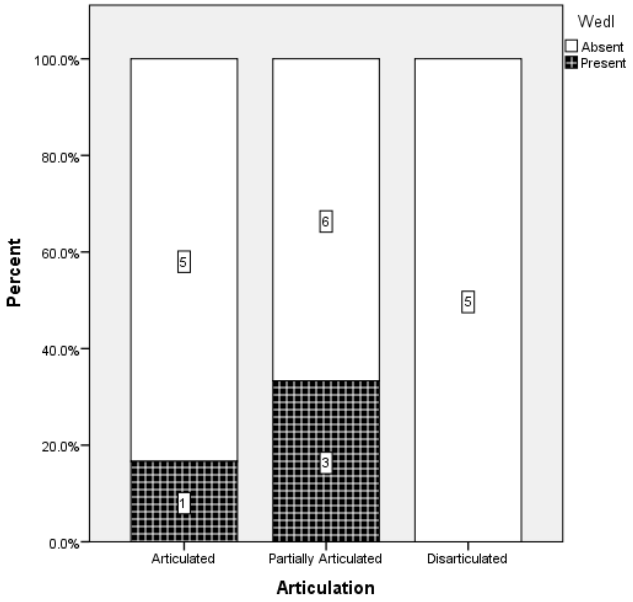

Figure 6.30: Proportional bar chart displaying the occurrence of Wedl tunnelling within Danebury & Suddern Farm samples from skeletons that demonstrated variable levels of articulation.

The periosteal surface had been lost in twelve out of the twenty samples from these sites, which represented a higher proportion than what was observed amongst the other site assemblages. Like bacterial bioerosion and Wedl tunnelling, the survival of the periosteal surface appeared to be linked to state of articulation (Figure 6.31). Samples of articulated and partially articulated bones were more likely to have lost their periosteal cortex than samples

from disarticulated skeletal elements. This result added to the evidence for the different treatment of the articulated/partially articulated and disarticulated bones.

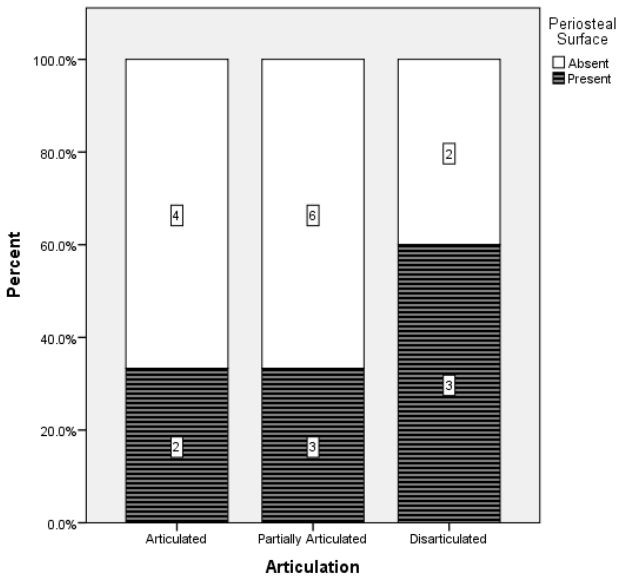

Figure 6.31: Proportional bar chart of the loss of the periosteal surface amongst Danebury & Suddern Farm samples from skeletons recovered in variable states of articulation.

Only three of the samples from Danebury and Suddern Farm demonstrated microstructural staining. In two cases this staining was extensive, and in one it was only superficial. The superficial staining was orange-coloured, whilst the extensive discolouration was orange and yellow respectively. Deposit 130 demonstrated extensive yellow staining and it was possible that this feature was related to its deviant taphonomic history. Grey inclusions appeared frequently or infrequently within most remains from Danebury and Suddern Farm. Infiltrations were not observed within any of the samples from this site.

The well-preserved sample from Deposit 130 demonstrated reduced levels of collagen birefringence that could not be explained by microbial bioerosion. The yellow discolouration of this sample had not rendered the bone opaque and could not have been responsible for the dampening of collagen birefringence. Collagen must have been lost from this bone through a mechanism other than biodegradation.

6.1.2.8 Frälsegården Neolithic Chambered Tomb, Falbygden, Sweden

Samples had been taken from articulated, partially articulated and disarticulated post-neonatal bones from Frälsegården. The histological preservation of the Frälsegården specimens was

quite poor. No thin section scored higher than three on the OHI scale and most scored two or below (Figure 6.32). However, there was considerable variation in Whole OHI score within this range. The distribution of Whole OHI scores amongst the Frälsegården samples was slightly skewed towards higher values when compared to the Historical baseline, but overall the two distributions were consistent with one another.

The distribution of Whole OHI scores from the Frälsegården specimens could be split between those samples that had no measurable microstructure remaining (OHI=0) and those that retained some detectable level of histological integrity (OHI>0). These groups were separated by state of articulation and phase. Samples taken from bones that had been partially or fully articulated dated to a later phase of activity and retained higher levels of microscopic preservation compared to the earlier disarticulated bone samples, which all demonstrated Whole OHI scores of zero (Figure 6.33).

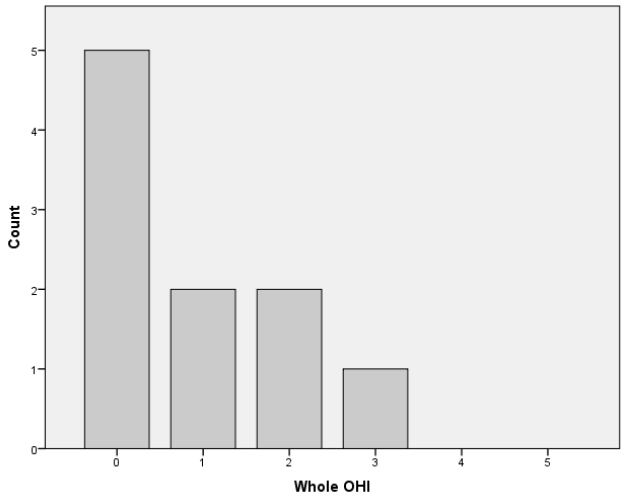

Figure 6.32: Frequency histogram of the distribution of Whole OHI scores amongst remains from the Frälsegården Neolithic chambered tomb.

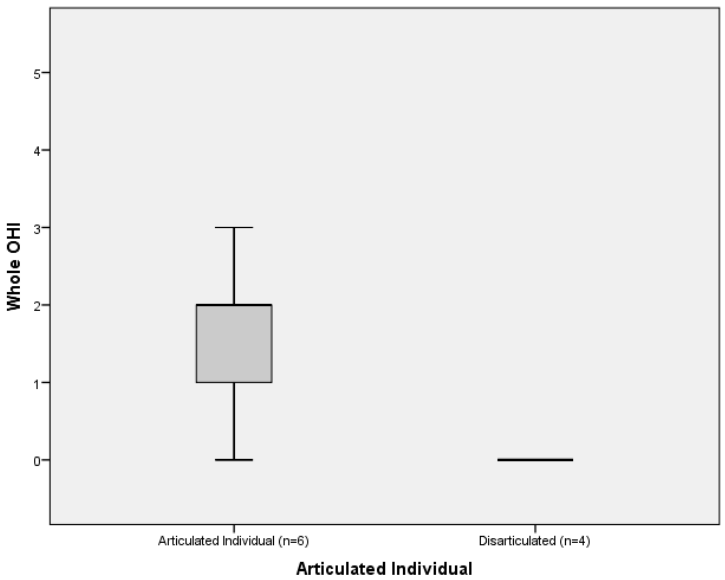

Figure 6.33: Distributions of Whole OHI scores amongst Frälsegården samples from skeletons that had been recovered in variable states of articulation.

The microstructures of five of the ten Frälsegården samples had been stained. Four of the samples demonstrated brown staining and one had been stained orange. This staining was only ever superficial. Orange inclusions were observed infrequently or frequently within eight of the Frälsegården thin sections. Infiltrations were present within seven of the ten Frälsegården bone samples.

6.1.2.9 Hornish Point Iron Age Settlement, South Uist, U.K.

The bone of the partially-articulated individual recovered from Hornish Point had been severely degraded by bacterial attack and was allocated a Whole OHI score of zero. The bacterial attack had consumed all of the available microstructure apart from the periosteal cortex. The Whole OHI score of the Hornish Point sample was consistent with the distribution of scores amongst the Historical baseline assemblage. The sample demonstrated some superficial orange staining at the periosteal and endosteal surfaces. Orange inclusions appeared infrequently within the Hornish Point sample. Infiltrations were entirely absent.

6.1.2.10 Langwell Farm Early Bronze Age Cist, Sutherland, U.K.

The sample from the adult articulated skeleton recovered from the Langwell Farm cist retained an excellent level of microstructural preservation and was free from microbial bioerosion. Microbial bioerosion was seldom absent from the bones included within the Historical baseline assemblage and the histological signature of the Langwell sample would have represented an outlier amongst this Historical baseline sample. There was evidence that the Langwell individual had decomposed within an anoxic environment. The histological preservation of this sample was consistent with the distributions of Whole OHI scores amongst the anoxic-deposited remains from Carver Street and Coronation Street, although the preservation of the Langwell sample was at the top of the range of the Historical anoxic-deposited distribution. The collagen birefringence of the Langwell sample had been reduced. Reductions in birefringence corresponded with areas of dark brown staining at the periosteal and endosteal surfaces. Orange inclusions appeared frequently within the Langwell sample, but infiltrations were absent. There was no orange discolouration of the bone microstructure within the Langwell sample (Hollund *et al.* 2012).

6.1.2.11 Neat's Court Bronze Age Round Barrow, Kent, U.K.

The Neat's Court bone samples were all from post-neonatal articulated or disarticulated skeletons. Three of the samples were histologically well-preserved, but the preservation of the remainder was poor (Figure 6.34). The degradation of these samples was predominantly attributable to non-Wedl tunnelling, although Wedl tunnels were identified in four samples. The Wedl tunnelling within the Neat's Court samples was more extensive than what was observed in most other specimens from the study sample that had been affected by this type of attack. However, Wedl tunnelling within the Neat's Court samples still occupied portions of the bone microstructure that were unaffected by bacterial MFD.

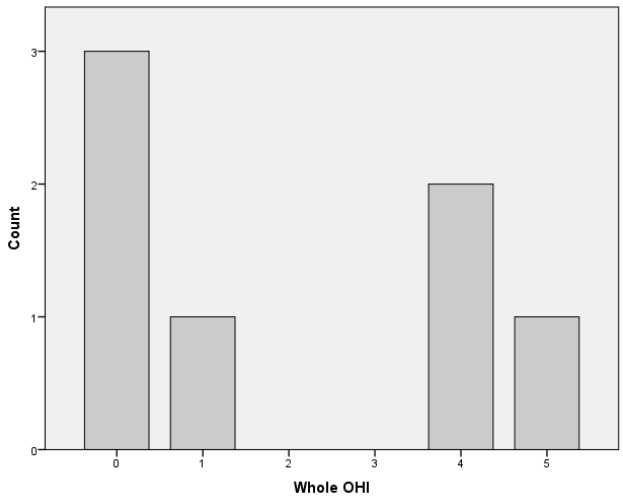

Figure 6.34: Frequency histogram of the distribution of Whole OHI scores amongst the remains recovered from the Neat's Court Bronze Age round barrow.

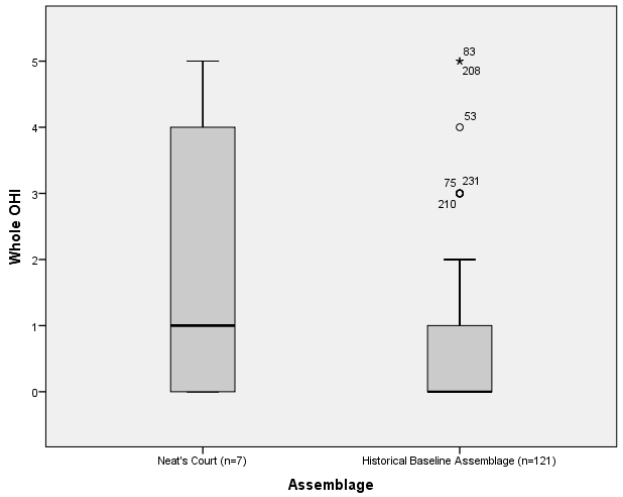

Figure 6.35: Distribution of Whole OHI scores amongst the Neat's Court samples compared to the Historical baseline assemblage.

The distribution of Whole OHI scores amongst Neat's Court remains was slightly elevated and variable compared to the Historical baseline, as defined by the median value and interquartile range (Figure 6.35). The Neat's Court samples that had been allocated Whole OHI scores of four and five were primarily responsible for the deviation of the distribution from the Historical baseline. Two of the Neat's Court samples were free from bacterial bioerosion. One of these samples demonstrated levels of fungal tunnelling which were responsible for a lower Whole OHI score of four. The single sample taken from the disarticulated skeleton had been extensively bioeroded.

Five of the seven skeletons that were sampled demonstrated macroscopic surface modifications that suggested they had been exposed to heat treatment. It was possible that the heat treatment represented a novel *post mortem* process (Morley personal communication 2012). The fire-treated remains demonstrated varied and elevated Whole OHI distributions compared to the bones that showed no heat alteration (Figure 6.36). All of the samples form Neat's Court demonstrated fair levels of orange discolouration. All samples included frequent or infrequent occurrences of orange inclusions. Infiltrations were present within all of the Neat's Court thin sections.

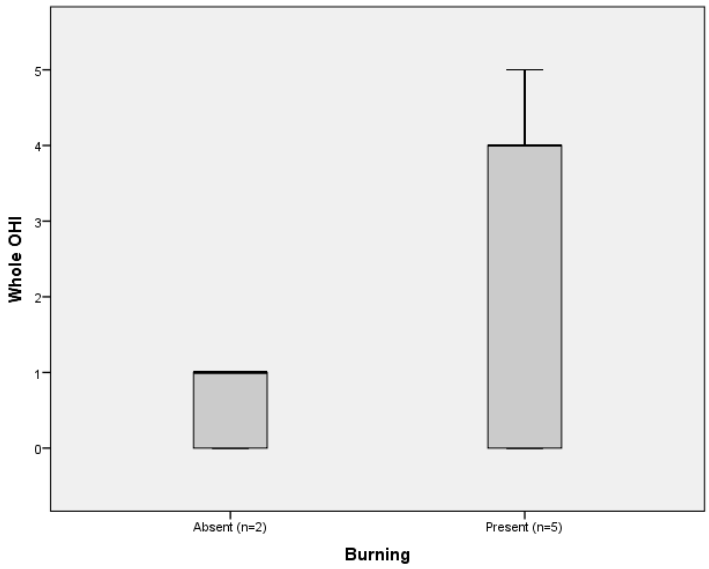

Figure 6.36: Distributions of Whole OHI score amongst Neat's Court samples from skeletons that variably demonstrated macroscopic signs of burning.

6.1.2.12 South Dumpton Down Bronze Age Round Barrow and Iron Age Settlement, Kent, U.K.

Articulated, partially articulated and disarticulated post-neonatal skeletons had been sampled from South Dumpton Down. All of these samples demonstrated poor levels of histological preservation due to bacterial tunnelling (Figure 6.37). The distribution of Whole OHI scores within the South Dumpton Down specimens was consistent with the Historical baseline. The modal Whole OHI score of the South Dumpton Down samples was one, which suggested that this assemblage as a whole demonstrated slightly higher levels of histological preservation than the Historical baseline. The best-preserved South Dumpton Down sample dated to the Iron Age, whilst the rest of the bones were associated with the Early Bronze Age barrow. Samples from articulated skeletons demonstrated slightly elevated distributions of Whole OHI scores compared to the disarticulated and partially articulated remains. However, the

articulated sub-set included the Iron Age skeleton, which may have been subjected to a different form of treatment than the Bronze Age bodies.

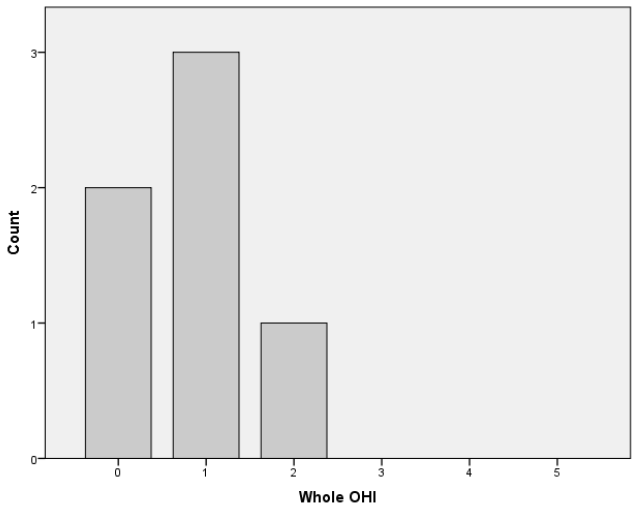

Figure 6.37: Frequency histogram of the distribution of Whole OHI scores amongst the remains sampled from the South Dumpton Down Bronze Age round barrow and Iron Age settlement.

Staining was only observed in one of the South Dumpton Down samples. This staining consisted of superficial brown discolouration at the periosteal and endosteal surfaces. Orange inclusions occurred frequently or infrequently within all of the South Dumpton Down samples. Infiltrations were absent from within this sample set.

6.1.2.13 Whitwell Quarry Neolithic Cairn, Derbyshire, U.K.

All four disarticulated bones sampled from the Whitwell Quarry assemblage demonstrated poor levels of histological preservation due to bacterial tunnelling and had been allocated Whole OHI scores of zero. The histological preservation of the Whitwell samples was consistent with baseline Historical samples. Two of the five Whitwell thin sections demonstrated superficial orange microstructural staining. Orange inclusions appeared infrequently within four out of the five samples. Infiltrations were detected in only one sample.

6.1.2.14 Windmill Fields Bronze Age Cemetery at Ingleby Barwick, County Durham, U.K.

The Ingleby Barwick samples had been taken from post-neonatal articulated and disarticulated skeletons. Two of the samples from articulated skeletons were scored the lowest Whole OHI scores of zero. The other two samples, taken from one articulated and one disarticulated skeleton, were both allocated the highest Whole OHI score of five. The two high-scoring remains were free from microbial bioerosion and would have represented outliers within the Historical baseline assemblage.

Histological preservation at Ingleby Barwick was not dependent on skeletal articulation. There was some patterning in the Whole OHI scores by phase. The later (Middle Bronze Age) remains were both badly degraded, whereas the bones that dated to the Early Bronze Age (Sk 2 and Sk 3) were histologically well-preserved. The relationship between collagen birefringence and histological preservation was inconsistent within the Ingleby Barwick thin sections. Some of the bones that retained high levels of histological preservation demonstrated reduced levels of collagen birefringence. These areas of birefringence reduction were coincident with brown microstructural staining. Areas of brown staining were apparent in the thin sections of the two well-preserved samples. Orange inclusions appeared infrequently within all of the remains from Ingleby Barwick. No infiltrations were recorded within the samples from this site.

6.2 Analysis of Assemblages from Specific Later Prehistoric Phases

The results of the Primary Analysis established that there were significant differences in distributions of Whole OHI scores between Later Prehistoric and the Historical baseline distribution. The distribution of Whole OHI scores amongst the Later Prehistoric assemblage was also significantly different from a normal distribution, which indicated that there was a substantial level of variation in the histological preservation of this assemblage that required explanation. The Later Prehistoric distribution of Whole OHI scores deviated from the normal model and the Historical baseline by the higher numbers of remains that had been allocated medium and high Whole OHI scores.

The only factor which came close to explaining some of the Later Prehistoric variation in histological preservation within the Primary Analysis was Specific Phase. Bronze Age samples tended to demonstrate higher rates of unbioeroded bones. It had been expected that if

bacterial bioerosion related to funerary treatment, there would be some variation in histological preservation within samples from different Later Prehistoric phases, because each phase potentially represented a cultural shift that was likely to be accompanied by changes in the ways the dead were treated. However, there were no significant differences in distributions of Whole OHI scores between bones from different Later Prehistoric phases. This result indicated that distributions of Whole OHI scores amongst remains from specific Later Prehistoric phases were likely to be significantly different from the Historical baseline and include unexplained variation. It was pertinent to explore phase-specific trends in histological preservation to determine whether this factor may explain overall Later Prehistoric variation in nuanced ways that may not have been detected by statistical techniques.

It was predicted in the Methodology that if bacterial bone bioerosion related to funerary activity then the majority of the variation in Whole OHI would have originated within the disarticulated remains of the Later Prehistoric assemblage. There was no significant difference in the distributions of Whole OHI score between articulated and disarticulated Later Prehistoric remains. This lack of significant difference meant that distributions of Whole OHI scores within articulated and disarticulated Later Prehistoric bone assemblages were significantly different from the Historical baseline model. It was pertinent to compare the results from the articulated and disarticulated Later Prehistoric assemblages against the Historical baseline sample in order to discern the nature of their variation. It was hoped that these results combined Specific Phase would contribute to the explanation of variance in bacterial bioerosion within the Later Prehistoric assemblage.

6.2.1 Neolithic Samples

After the neonatal and anoxic-deposited remains were disregarded, large proportions of Neolithic samples demonstrated the lowest OHI scores of zero, which was consistent with the Historical baseline assemblage (Figure 6.38). However, the Neolithic distribution deviated from the Historical baseline by the proportions of samples allocated Whole OHI scores of two and, to a lesser extent, five. These deviations constituted part of the significant variation in Whole OHI score within the Later Prehistoric bones. Only disarticulated Neolithic samples had been allocated Whole OHI scores of five. One of these samples was from the Ingleby Barwick wooden cist deposit that was later found to date to the Bronze Age. Another one of these histologically well-preserved samples had been taken from the Carsington Pasture Cave cut

marked bone. The few articulated Neolithic bone samples demonstrated a Whole OHI score profile that was consistent with the Historical baseline. The rest of the disarticulated remains were responsible for the main peak at zero, and the slight peak at two.

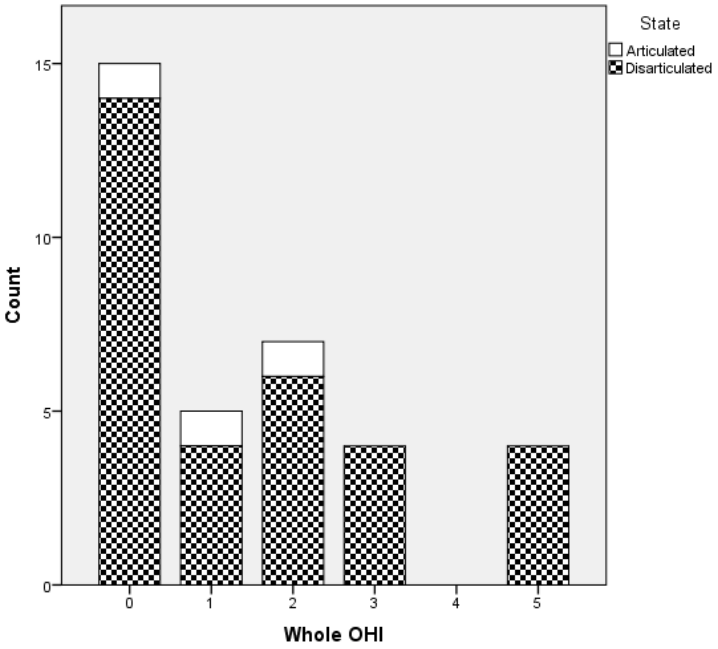

Figure 6.38: Distribution of Whole OHI scores amongst the Neolithic samples separated by state of articulation (neonatal remains were excluded).

6.2.2 Bronze Age Samples

The distribution of Whole OHI scores amongst the post-neonatal Bronze Age remains from aerobic environments differed from the Neolithic distribution. The Bronze Age remains included the familiar large peak at Whole OHI scores of zero (Figure 6.39). Frequencies of samples declined through Whole OHI scores of one, two and three, which was consistent with the Historical baseline model. However, the proportions of Bronze Age bone samples that had been allocated Whole OHI scores of four and five produced a second peak that rivalled the first, creating a bimodal distribution. The Bronze Age remains were largely responsible for the high Whole OHI scores within the Later Prehistoric distribution. This trend was reflected within the finding that the Bronze Age assemblage included higher proportions of remains that were free from bacterial bioerosion. There was no division by state of articulation between the histologically poorly-preserved and well-preserved Bronze Age samples. Histologically well-preserved samples were just as likely to have originated from an articulated or disarticulated skeleton.

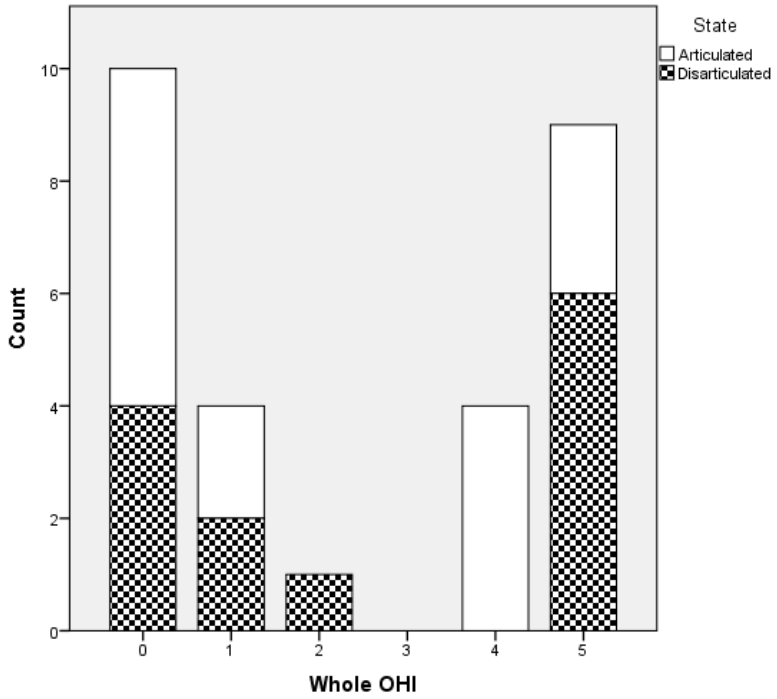

Figure 6.39: Distribution of Whole OHI score amongst the Bronze Age remains separated by state of articulation (anoxic-deposited remains were excluded).

6.2.3 Iron Age Samples

The distribution of Whole OHI scores amongst the Iron Age sample assemblage also differed subtly from those of the Neolithic and Bronze Age assemblages. The dominant peak at Whole OHI scores of zero was present but there was another equivalently large peak at Whole OHI scores of two (Figure 6.40). The Iron Age assemblage was predominantly responsible for the peak at Whole OHI scores of two within the Later Prehistoric remains taken as a whole. The Iron Age assemblage did not demonstrate a notable proportion of remains that retained high Whole OHI scores, which set it apart from the Neolithic and Bronze Age assemblages. Both articulated and disarticulated Iron Age samples that had been allocated Whole OHI scores of between zero and three. A single disarticulated sample had been allocated the highest Whole OHI score of five.

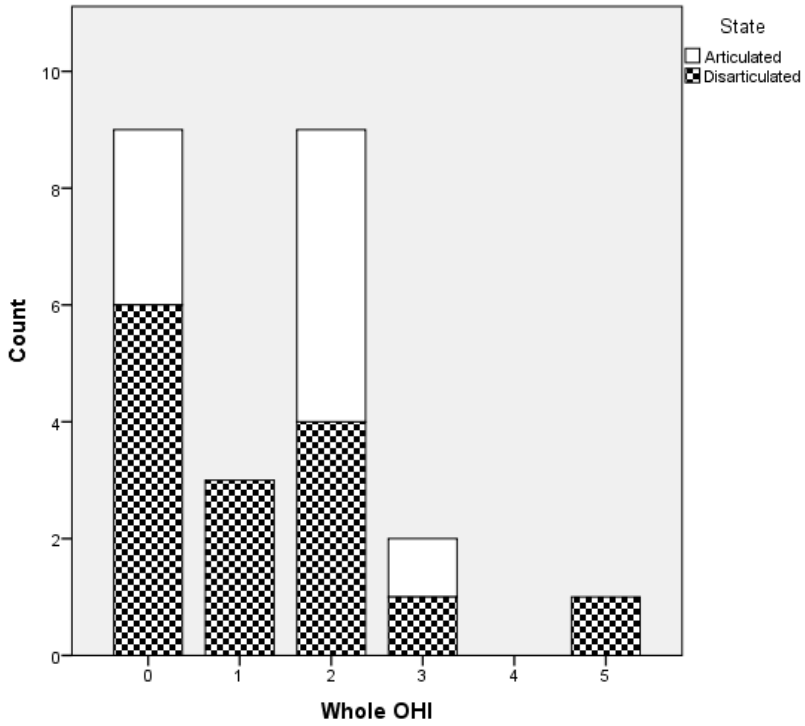

Figure 6.40: Distribution of Whole OHI scores amongst the Iron Age samples separated by state of articulation.

6.2.4 Interactions between State, Specific Phase and Bacterial Bioerosion

The relationships between Specific Phase, state of articulation and Whole OHI score were complex. There were subtle differences between distributions of Whole OHI scores amongst assemblages from different Later Prehistoric phases. The majority of articulated remains from Neolithic and Iron Age sites demonstrated consistently low levels of histological preservation (Figure 6.41). However, these levels of histological preservation were slightly elevated compared to the Historical baseline, particularly with respect to the bone samples that had been allocated Whole OHI scores of two. All of the articulated Later Prehistoric remains that demonstrated the highest Whole OHI scores belonged to the Bronze Age. Articulated remains that were allocated Whole OHI score of 4 or 5 were recovered from three of the four Bronze Age sites that were included within this distribution.

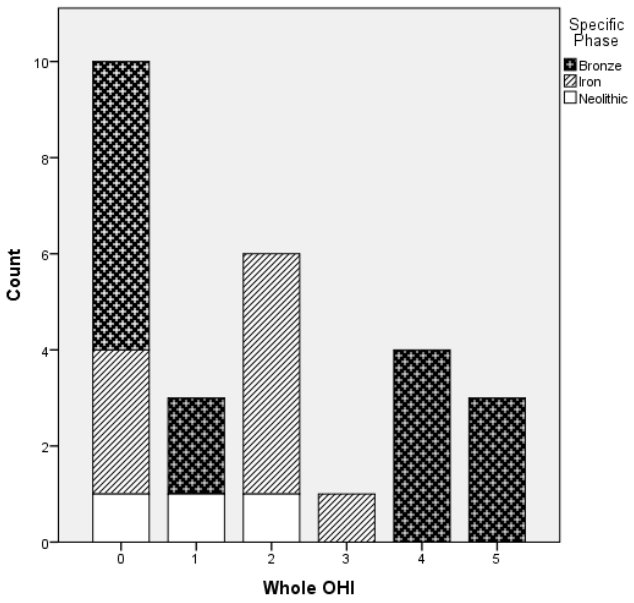

Figure 6.41: Distribution of Whole OHI scores amongst Later Prehistoric samples from articulated skeletons separated by Specific Phase (neonatal and anoxic-deposited remains were excluded).

Distributions of Whole OHI scores amongst the disarticulated Later Prehistoric sample assemblage organised by phase were more balanced (Figure 6.42). Every specific phase was represented amongst most of the Whole OHI scores that appeared. Histological preservation amongst the disarticulated remains was more variable than amongst the samples from articulated skeletons, and was not defined by Specific Phase to the same extent.

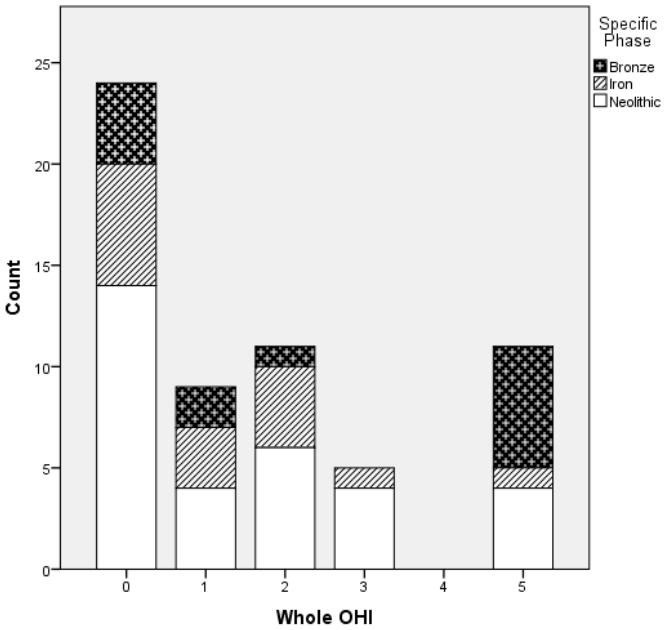

Figure 6.42: Distribution of Whole OHI scores amongst Later Prehistoric samples from disarticulated skeletons separated by Specific Phase (neonatal and anoxic-deposited remains were excluded).

6.3 SUPPLEMENTARY ASSEMBLAGES

The supplementary samples were examined in order to complement the analysis of the primary assemblage, and were considered separately. Only small numbers of samples were obtained from each supplementary site. Some of the supplementary remains included diagenetic phenomena that had not been observed within the primary assemblage. Therefore, analysis of the results from these sites is mostly descriptive.

6.3.1 Havnø Mesolithic/Neolithic Shell Midden

The histological preservation of the Havnø samples was highly variable (Figure 6.43). Most Whole OHI categories were represented, although there was a bias towards higher values. All but three of the samples from Havnø demonstrated evidence for bacterial bioerosion. None of the samples had been taken from neonatal skeletons. All samples, including those that had been extensively altered by bacteria, retained bands of well-preserved circumferential lamellar bone at their periosteal fringe.

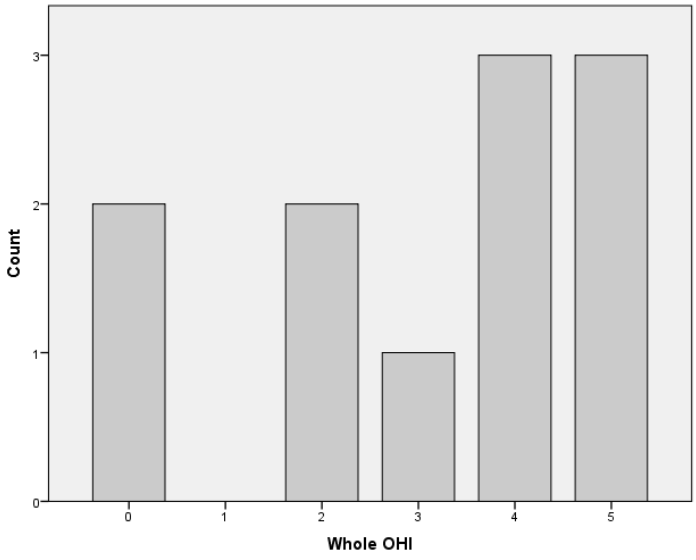

Figure 6.43: Frequency Histogram of the distribution of Whole OHI scores amongst the remains from the Neolithic-Mesolithic Havnø shell midden.

The primary aim of sampling the disparate bones from the Havnø assemblage was to establish whether bacterial bioerosion varied with skeletal element and/or anatomical location. There were no statistically significant differences in the Whole OHI scores amongst different skeletal

elements (n=11, K-W Chi-squared=4.782, p=0.572). Replicate skeletal elements always demonstrated disparate levels of bacterial bioerosion. The two metatarsal samples lay on opposite ends of the OHI scale from one another. Some of the skeletal elements were represented by only one sample. There was no significant relationship between the presence of bacterial bioerosion and skeletal element (Pearson's chi-squared, n=11, Fisher's Exact=5.221, p=0.927).

When bone samples from particular parts of the body were grouped together and compared there was still no significant distribution of Whole OHI scores between sample groups (n=11, K-W chi-squared=0.206, p=0.902). Whole OHI scores within bones from different parts of the body varied considerably and did not decrease with proximity to the gut. Levels of bacterial bioerosion were not dictated by skeletal part or anatomy. There was also no significant difference in the occurrence of bacterial bioerosion within bones from different anatomical sites (Pearson's chi-squared, n=11, Fisher's Exact=0.803, p=1.000). Most of the remains from Havnø demonstrated similar orange and brown inclusions. Patches of light brown staining appeared inconsistently within the osteonal bone of most thin sections, whilst orange staining concentrated at the periosteal and endosteal peripheries appeared infrequently.

6.3.2 Mummified Samples

The status of the mummified remains as single specimens taken from discrete sites meant that the results of the histological analysis of their thin sections could not be analysed statistically. Therefore the results from the mummified samples are discussed descriptively.

6.3.2.1 Derrycashel Bog Body

Samples of the Derrycashel body's tibia and clavicle were thin sectioned. Both thin sections had been stained a vivid deep red colour, which diffused to black towards the outer fringes (Image 6.2). Both samples demonstrated excellent levels of microstructural preservation and collagen birefringence (Image 6.3). This sample would have represented an outlier within the Historical baseline distribution. There were sporadic occurrences of dark tunnels visible in all of the Derrycashel thin sections but more commonly within the tibial samples. These isolated tunnels resembled enlarged osteocyte lacunae. There was an obliteration of collagen

birefringence associated with the tunnelling when the sections were viewed under polarised light (Image 6.4). The enlarged lacunae were observed to have grown and coalesced in certain places, forming larger dark areas of destruction (Image 6.5). The accumulated erosion was sometimes of a similar size and shape to non-Wedl MFD.

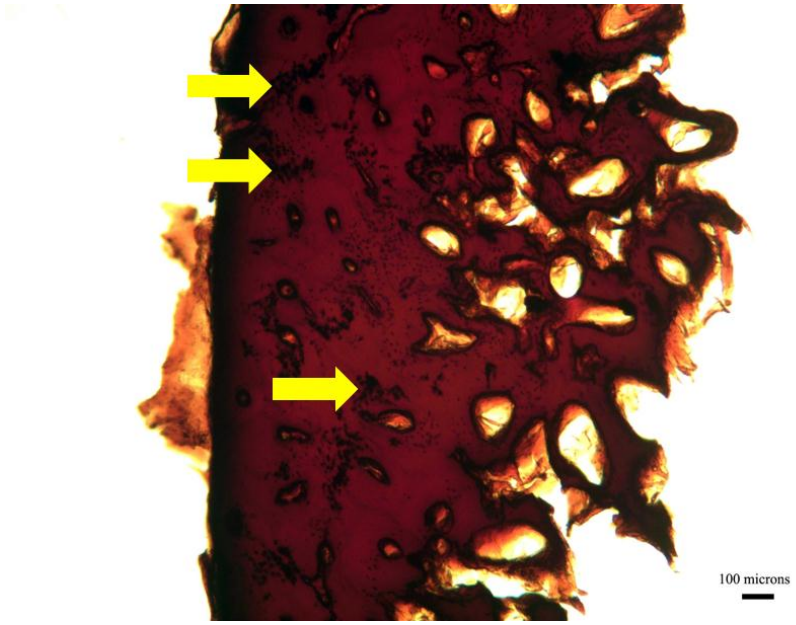

Image 6.2: Micrograph of a tibial thin sections from the Derrycashel bog body. The bone has been stained a deep red colour. The histological structure of the sample is well-preserved, although small accumulations of focal collagen loss can be observed throughout, particularly surrounding osteons (yellow arrows).

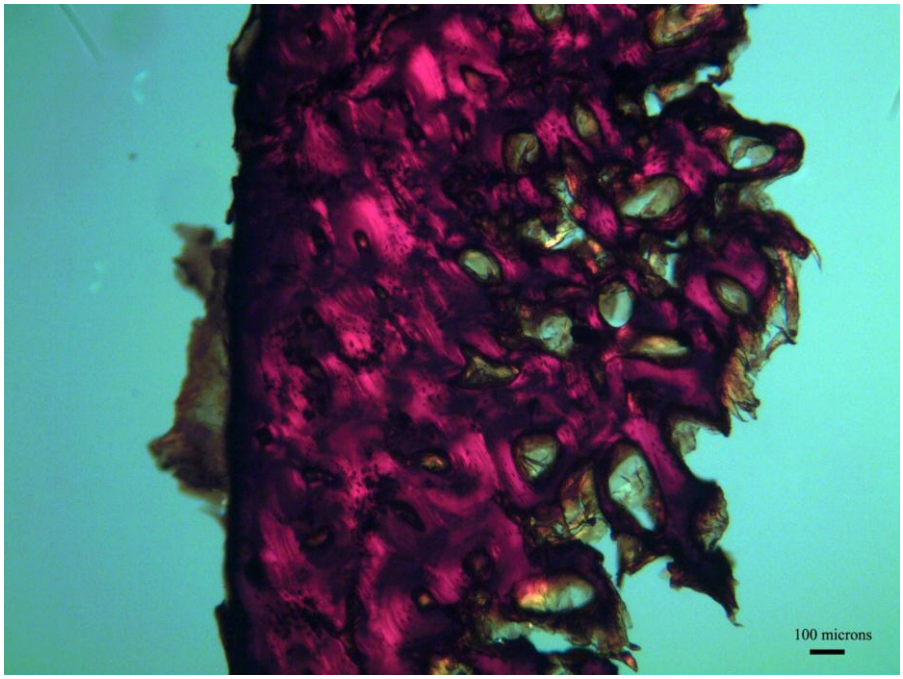

Image 6.3: Micrograph of a tibial thin section from the Derrycashel bog body viewed under polarised light. Collagen birefringence has been preserved.

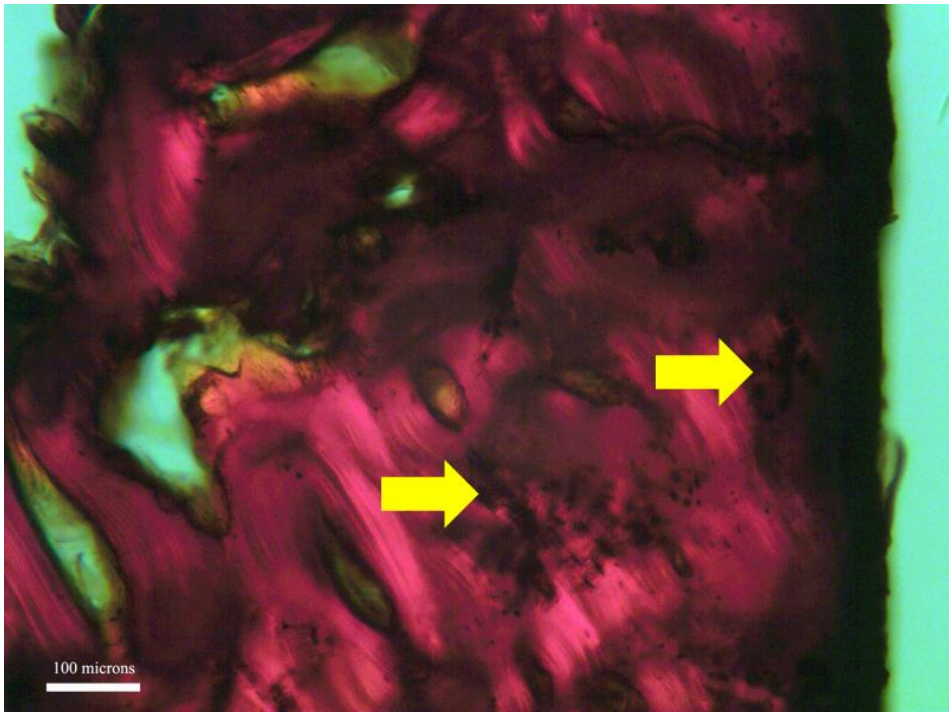

Image 6.4: Micrograph of a tibial thin section from the Derrycashel bog body under polarised light. Focal points of collagen loss can be seen to interrupt collagen birefringence (yellow arrows).

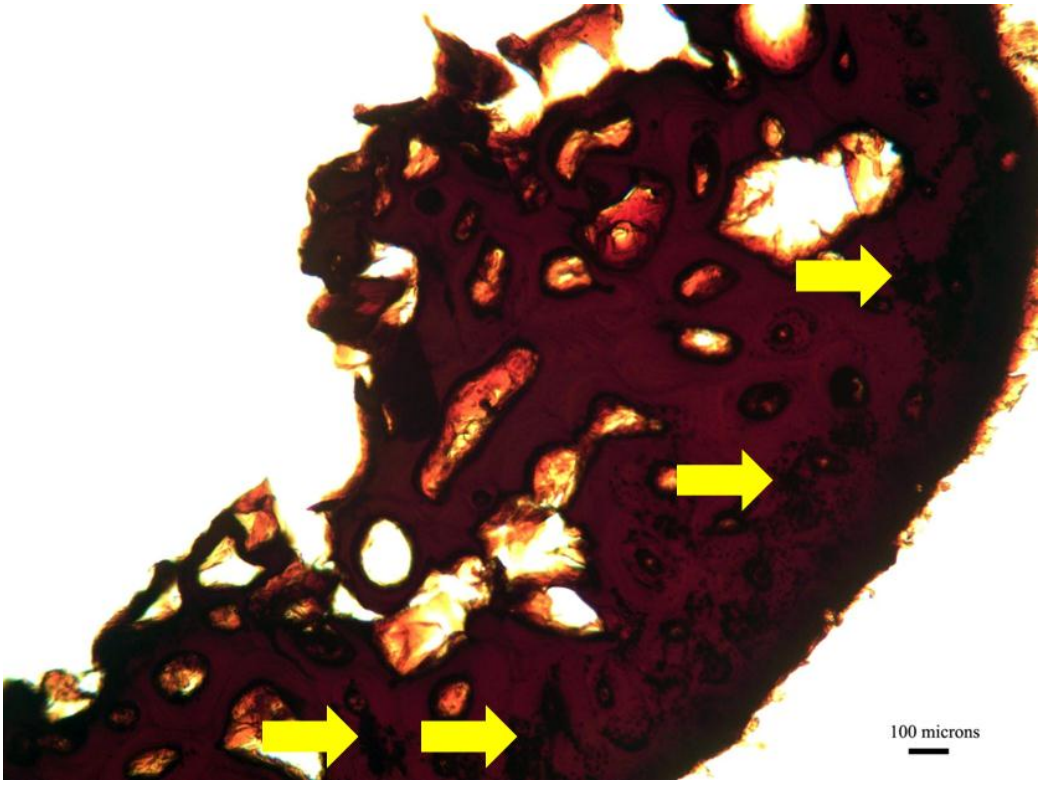

Image 6.5: Micrograph of a tibial thin section from the Derrycashel bog body. The enlarged osteocyte lacunae-like focal points of collagen loss can be observed to have accumulated, creating larger diagenetic forms (yellow arrows).

Characteristic hypermineralised rims were absent from these MFD-like agglomerations (Hackett 1981). These lesions never covered enough of the bone microstructure for the destruction to have been registered by the OHI system. The tunnelling appeared sporadically throughout the thin sections, but was concentrated towards the periosteal surfaces. Apart from the enlarged structures discussed above, there was a dearth of osteocyte lacunae within the Derrycashel thin sections. The deficit in lacunae was observed in all of the Derrycashel samples, but particularly within the clavicular sections (Image 6.6).

Dark, irregular-shaped inclusions were often observed lying within the natural Haversian canals of most of the Derrycashel thin sections (Image 6.7). These inclusions occurred more frequently within the tibial samples. The inclusions were often seen adhering to the periosteal and endosteal surfaces of bone thin sections. The opacity of these inclusions made it difficult to examine their structure for detailed description and identification. In certain instances the dark material crossed the boundaries of the Haversian canals and infiltrated the bone microstructure. There was no direct relationship between this infiltration and the focal destruction mentioned above. Most Haversian canals and other natural bone porosities contained orange translucent structures that lined or covered their respective cavities. These structures became illuminated under polarised light.

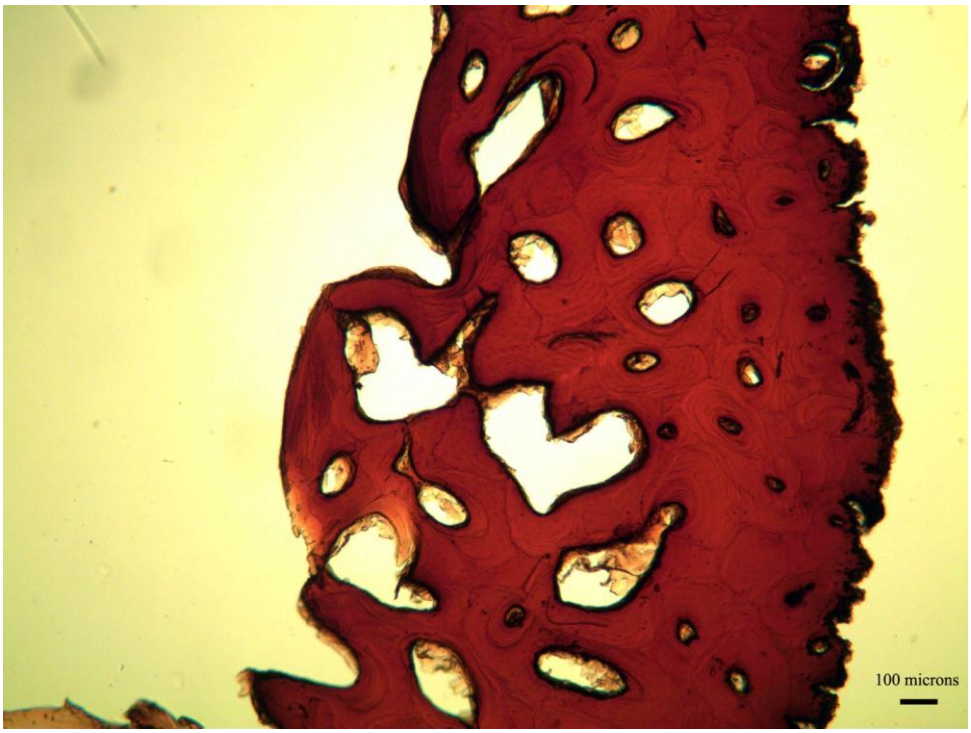

Image 6.6: Micrograph of a clavicular thin section from the Derrycashel bog body. There is a notable absence of osteocyte lacunae surrounding Haversian canals. Circular lamellar fibres that constitute osteons can be seen clearly (taken by the author).

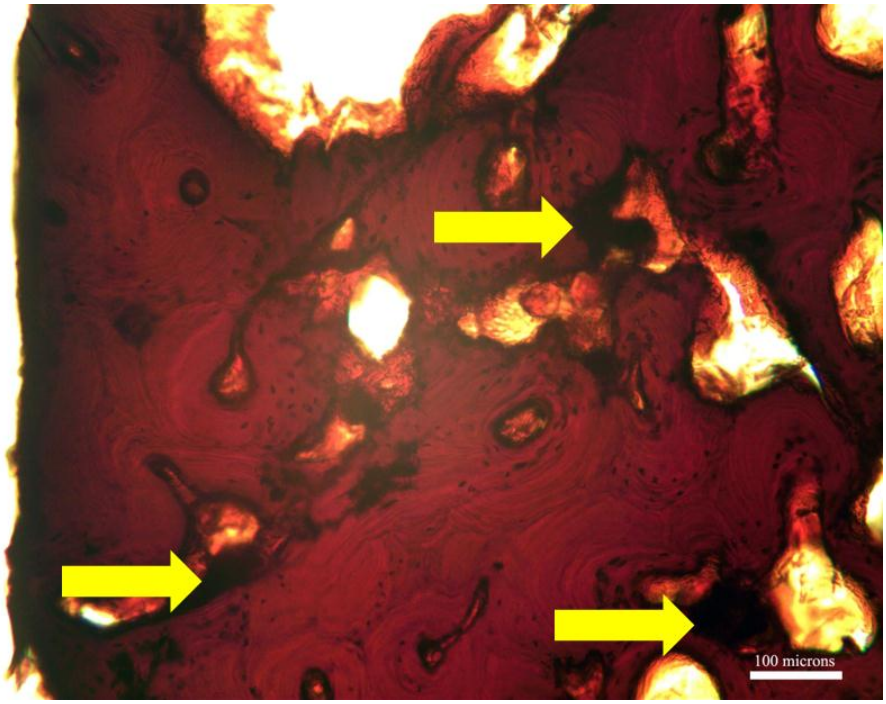

Image 6.7: Micrograph of a tibial thin section from the Derrycashel bog body. Irregular black inclusions can be observed within the natural porosities (yellow arrows).

6.3.2.2 Desiccated Yemeni Mummy

The histological preservation of the Yemeni patella was comparable to the modern dissection room sample and was classified as excellent (OHI=5) (Image 6.8 &Image *6.9*). Both the mummified and fresh sample retained high levels of collagen birefringence (Image 6.10). However, collagen birefringence within the mummified sample was diminished slightly towards the periosteal surface. The loss of birefringence in these areas had occurred in spite of the retention of high levels of microstructural preservation and indicated that collagen had been lost via a non-biological mechanism. The histological preservation of the Yemeni sample ensured that it would have been anomalous when compared to the Historical baseline distribution. The thin section of the archaeological patella was filled with non-Wedl MFD (OHI=0), which proved that this skeletal element was just as susceptible to microbial bioerosion as all other bones (Image 6.11).

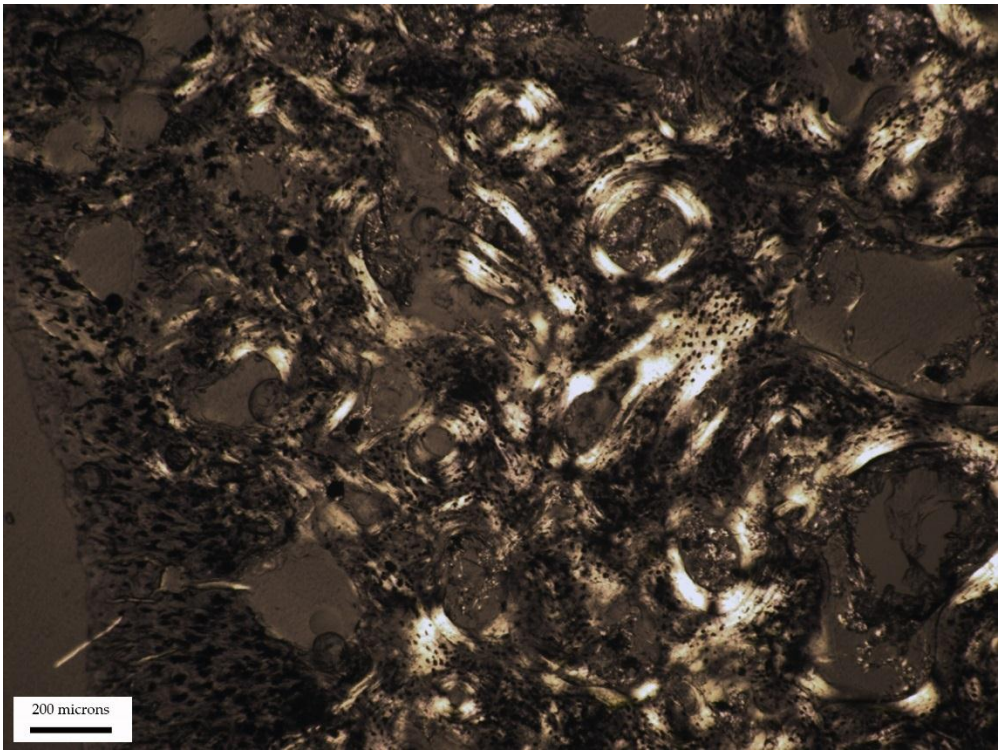

Image 6.8: Micrograph of a transverse thin section of a fresh patella of unknown provenance viewed under polarised light. Collagen birefringence is high, suggesting good preservation of organic structure.

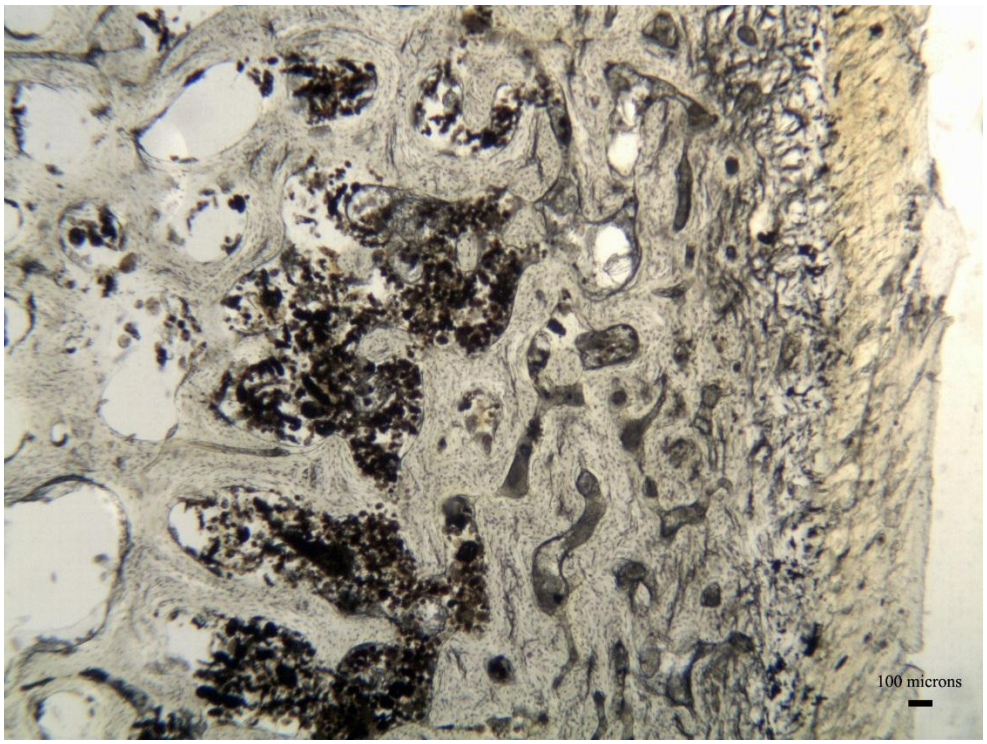

Image 6.9: Micrograph of a thin sections from the mummified Yemeni patella. The histological preservation of this sample was excellent. All major microstructures including osteons and osteocyte lacunae could be observed. The pale orange structure at the periosteal edge to the right of the image represented preserved soft tissue.

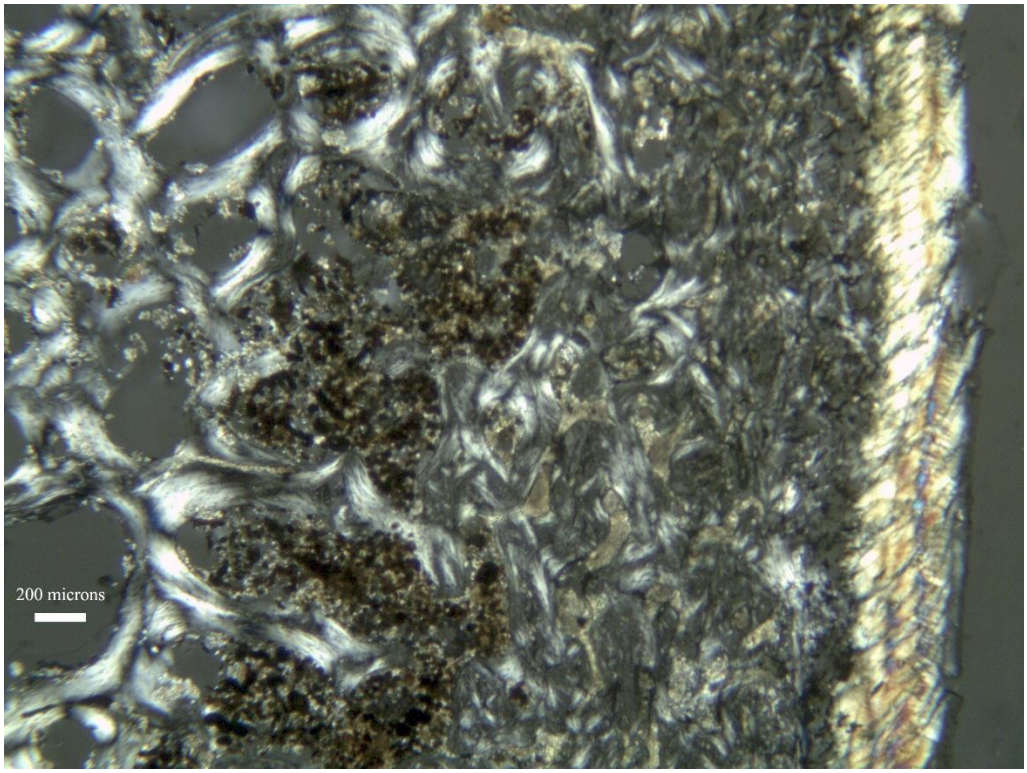

Image 6.10: Micrograph of a thin section from the mummified Yemeni patella. Collagen birefringence has been preserved throughout the bone microstructure but can be seen to diminish slightly towards the periosteal surface. The protein fibres within the preserved soft tissue at the periosteal surface were illuminated under polarised light.

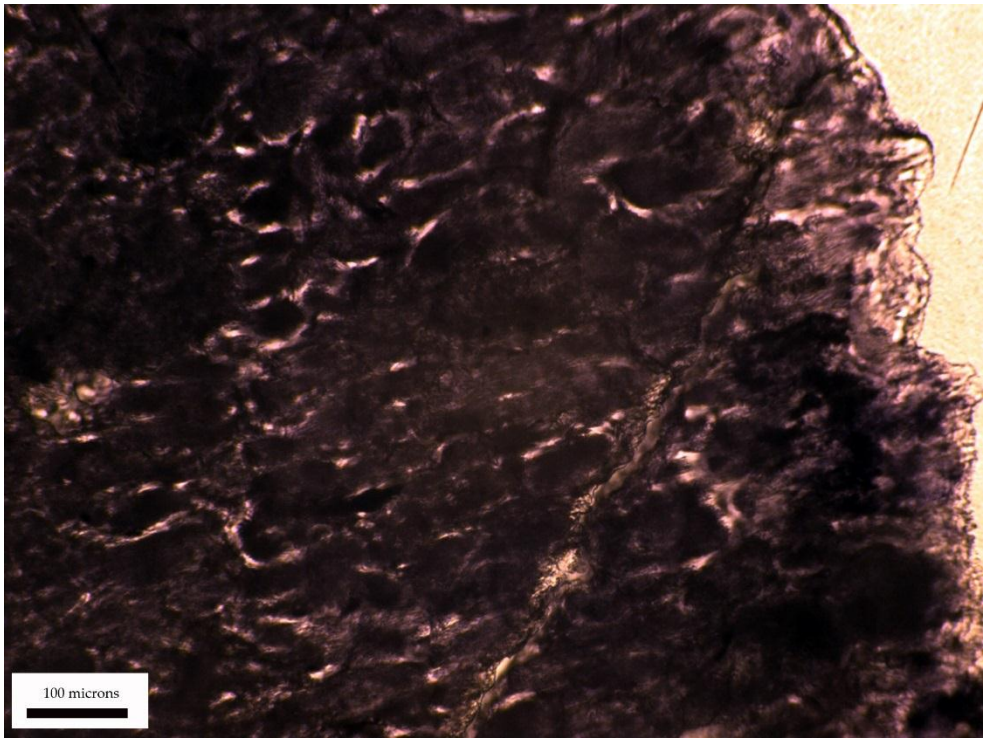

Image 6.11: Micrograph of a transverse thin section of the periosteal surface of an archaeological patella of unknown provenance. The microstructure has been extensively tunnelled by bacteria (taken by the author).

Small focal points of collagen loss could be observed towards the periosteal surface of the mummified patella, at the point at which the mummified soft tissue met with the bone (Image 6.12). This collagen loss resembled enlarged osteocyte lacunae and were similar to the lesions observed within the Derrycashel samples. These features covered a much smaller area of bone within the Yemeni sample and had not amalgamated into larger forms (Image 6.13). The enlarged osteocyte lacunae interrupted collagen birefringence when the sections were viewed under polarised light (Image 6.14).

Orange/brown and transparent particles were observed infrequently within the natural porosities of the mummified patella (Image 6.15). The soft tissue that adhered to the periosteal surface of the patella was an orange colour, but no staining was observed within the bone microstructure itself. No infiltrations were observed within this sample. The mummified patella demonstrated a notable excess of irregular, joined-up system of microfissures, particularly towards the junction between the bone and the soft tissue (Image 6.16). The presence of these microfissures sometimes corresponded with areas of dampened collagen birefringence (Image 6.17).

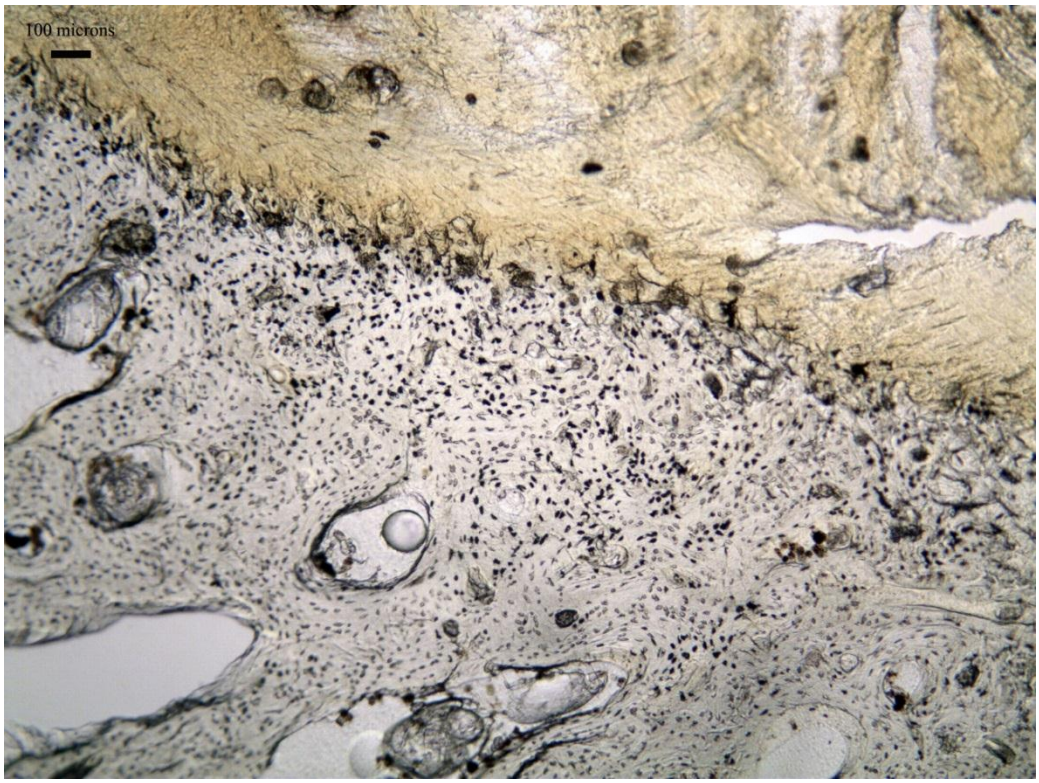

Image 6.12: Micrograph of a thin section from the mummified Yemeni patella. Small black focal points destruction resembling enlarged osteocyte lacunae can be observed towards the periosteal surface, close to the juncture between the bone and the soft tissue.

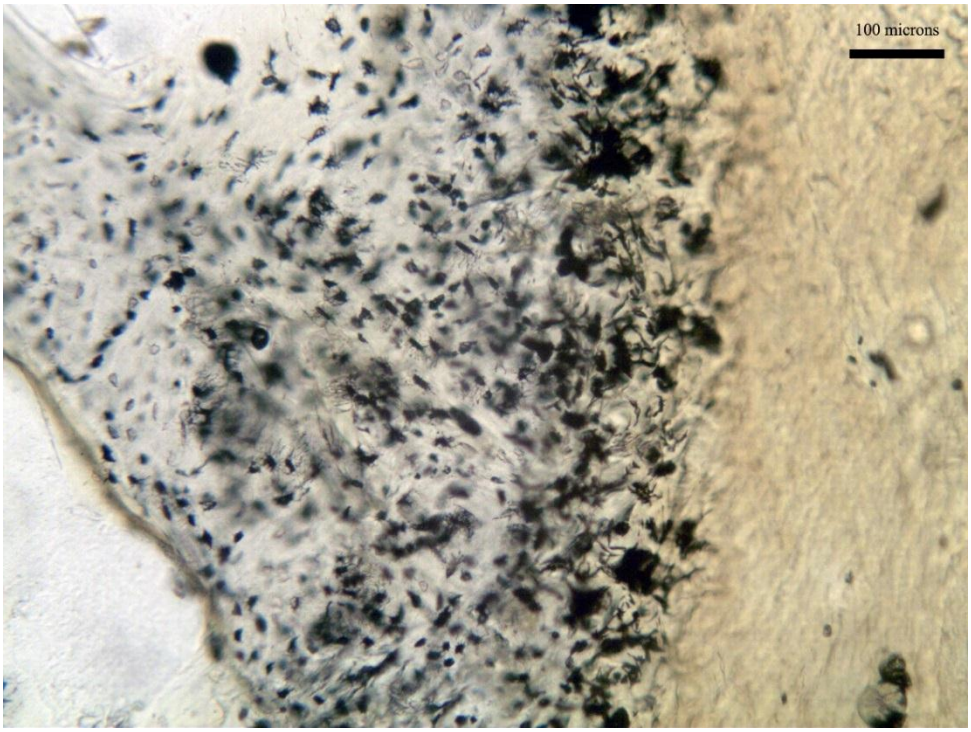

Image 6.13: Micrograph of a thin section from the periosteal surface of the Yemeni mummified patella. Accumulations of focal destruction of the bone microstructure can be observed at the juncture between the bone and the preserved soft tissue.

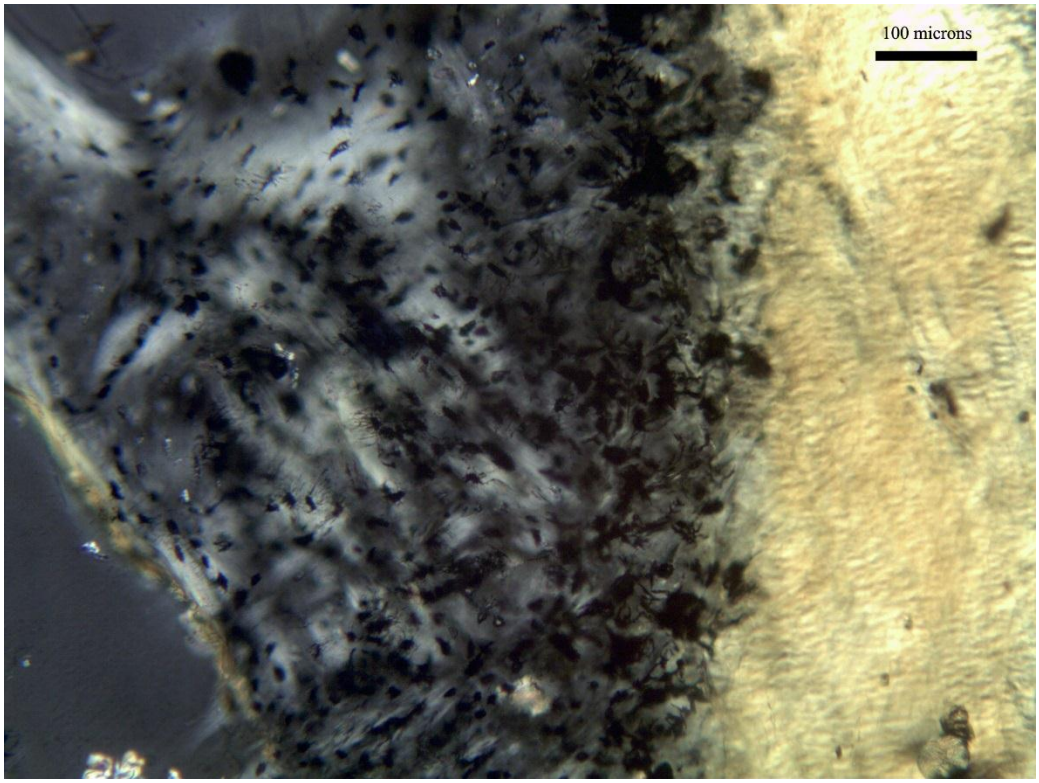

Image 6.14: Micrograph of a thin section from mummified Yemeni patella. The focal points of collagen loss have interrupted collagen birefringence.

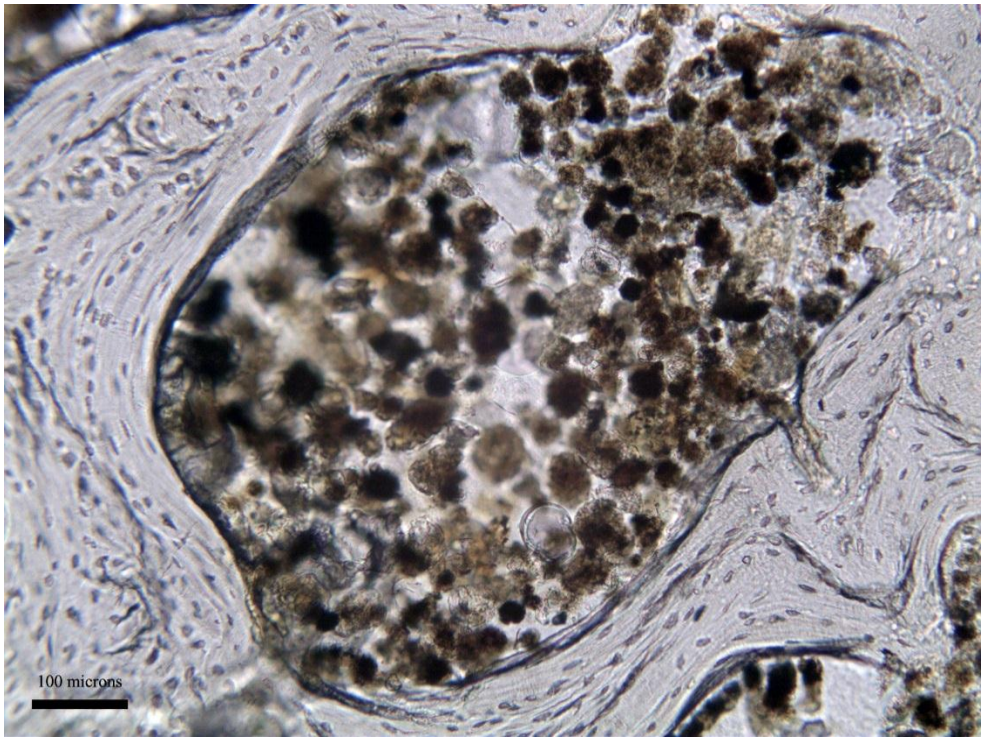

Image 6.15: Micrograph of a natural trabecular porosity within a thin section from the Yemeni mummified patella. Brown inclusions have filled the porosity.

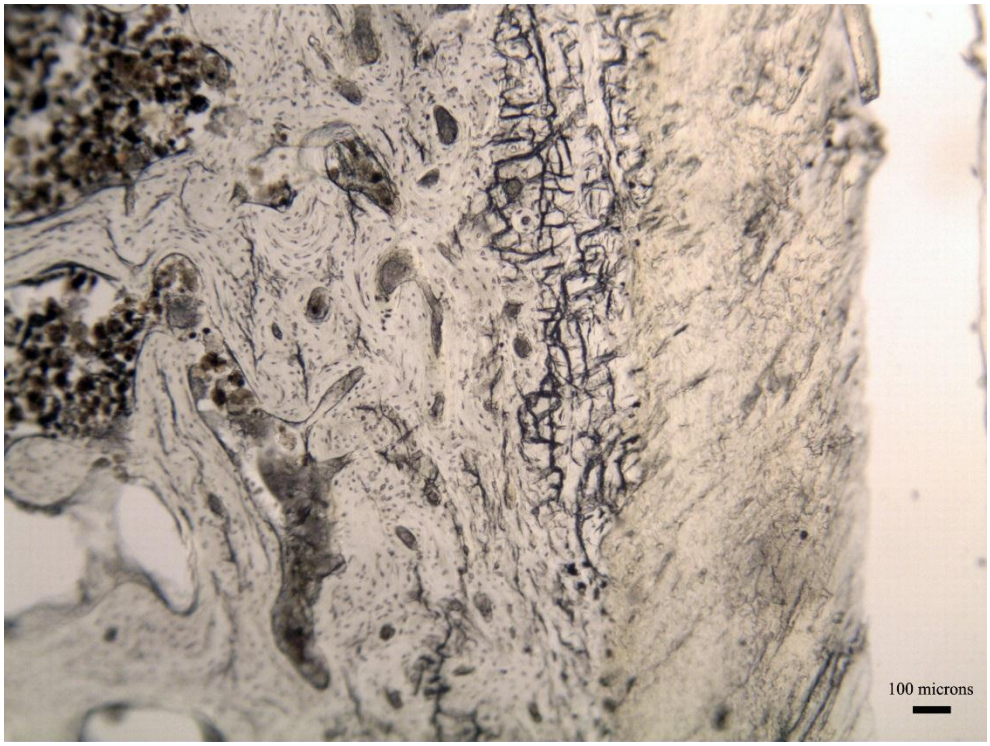

Image 6.16: Micrograph of the periosteal surface of a thin section from the Yemeni mummified patella. Microfissuring can be observed at the periosteal zone, at the juncture between bone and soft tissue.

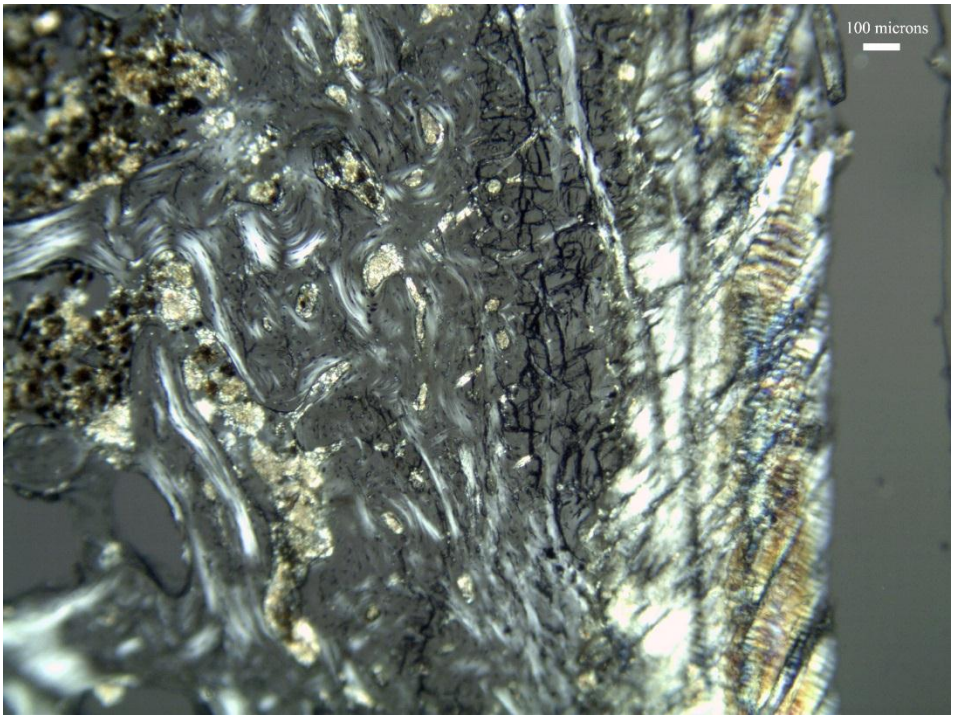

Image 6.17: Micrograph of the periosteal surface of a thin section from the Yemeni mummified patella. A loss of collagen birefringence at the periosteal surface can be seen to correspond within a microfissured area of bone microstructure.

An Investigation into the Relationship between Bone Diagenesis and Funerary Treatment.

Volume II

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Submitted for the Degree of Doctor of Philosophy

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University of Sheffield

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7 DISCUSSION

The Primary Analysis (first Results chapter) was geared towards addressing the research questions set out in the Background chapter (page 3). The following discussion is predominantly concerned with the results from this part of the analysis. However, this discussion will also encompass and amalgamate salient results from the Site Specific, Phase Specific and Supplementary Analyses. The Results chapters had expounded the findings from measures of physical bone degradation and visual diagenetic changes separately. The same pattern is followed in this discussion because of the established convention and also because the results had suggested that these two types of parameters had gauged separate influences of diagenetic change. The results from the mummified material are presented as isolated reports within a third and final section.

7.1 BONE DEGRADATION

The first part of this discussion focuses on the variation in measures of bone degradation; bioerosion (non-Wedl and Wedl), collagen birefringence and persistence of the periosteal surface. These discussions provide reasoning for the relationships between these parameters as well as the factors that had affected their variation. The results from each parameter are presented thematically, with separate discussions of the likely causes of particular relationships covered in order of diminishing significance. The predicted relationship between bacterial bioerosion and funerary process had been explained in the form of detailed hypotheses set out in the Background chapter (page 98). Interpretations of relationships between bacterial bone bioerosion and funerary treatment were framed with reference to these statements. Interpretations of variation amongst other measures of bone degradation were related to the research aims through discussions of observed correlations between diagenetic parameters and explanatory variables. Discussion of these results allows for some interpretation of the use of these features in reconstructions of early taphonomic processes.

7.1.1 Bacterial Bioerosion

The ubiquity of bacterial bioerosion within the bones used in the present study was consistent with observations by Jans *et al.* (2004) as well as other authors (Nielsen-Marsh & Hedges 2000; Turner-Walker *et al.* 2002; Jans *et al.* 2004; Nielsen-Marsh *et al.* 2007; Smith *et al.* 2007). The high proportion of bones sampled for the current project (87%) that had been bioeroded by bacteria was higher than the 75% rate of bioeroded archaeological human bones recorded by Jans *et al.* (2004: 89). The following discussion includes results from both Whole OHI measurement and the presence of bacterial bioerosion, as these measures complemented one another in representing the nature of biodeterioration found within particular bone assemblages.

7.1.1.1 Zonal OHI Scores

Zonal OHI scores were recorded because bacterial bioerosion across thin sections has been noted to vary (Hanson & Buikstra 1987; Hedges *et al.* 1995; Hedges 2002). All of the zonal OHI scores correlated significantly with Overall OHI score. This result suggested that all four measures of internal histological destruction were influenced by the same factors and could be taken to represent manifestations of the same process. The correlations between Whole OHI, Periosteal OHI and Endosteal OHI were lower than those between the Whole OHI and Internal OHI. The middle third of a thin section provides the best overall indication of histological integrity across the whole sample.

The differences between the distribution of Zonal OHI and Whole OHI scores were complex. Higher proportions of internal thirds demonstrated elevated Whole OHI scores compared to the endosteal and periosteal zones. Lower OHI scores allocated to the periosteal and endosteal thirds of thin sections were consistent with results of previous studies which have suggested that non-Wedl MFD form initially within sub-periosteal and sub-endosteal areas (Hanson & Buikstra 1987; Bell *et al.* 1996; Hedges 2002; Jans *et al.* 2004; Parker Pearson *et al.* 2005; Turner-Walker 2012). These areas of attack expanded internally until they meet within the middle third of the section (Hanson & Buikstra 1987; Bell *et al.* 1996; Hedges 2002; Jans *et al.* 2004; Parker Pearson *et al.* 2005; Turner-Walker 2012). This progression ensured that the internal third of a thin section was most often preserved within samples that demonstrated

limited levels of bioerosion. Even within heavily bioeroded samples, small islands of preserved bone microstructure were often observed within the internal third of thin sections.

Higher proportions of periosteal thirds of thin sections were scored OHI values of one and two, compared with endosteal zones, which tended to score zero. This difference was attributable to the persistence of the periosteal cortex, which served to elevate OHI scores in these zones. Preserved endosteal surfaces were not observed as often, although the endosteal cortex lies at the edge of the trabecular bone that is often lost during the thin sectioning process. It was possible that the lower Whole OHI scores of endosteal thirds of thin sections was due to a systematic loss of the endosteal trabecular fringe.

7.1.1.2 Whole OHI & Presence of Bacterial Bioerosion

The distribution of the Whole OHI scores towards low values suggested that no significant systematic bias had been introduced by the inequality of OHI categories (Hedges *et al.* 1995: Millard 2001). The inequalities involved with the OHI scoring system would have biased distributions towards scores of two and three. The results of the current study supported the two conclusions of Hedges *et al.* (1995: 203), that bacterial bioerosion within archaeological bones is generally distributed bimodally towards low and high levels of histological preservation and that when bacterial bioerosion begins, it usually continues until most of the bone microstructure has been destroyed. The modal Whole OHI values amongst the samples used in the present study were not as balanced as within the distribution presented by Hedges et al (1995: 203). Bones that demonstrated high levels of histological preservation were less common within the samples included in the current study. Higher proportions of samples used in the current study demonstrated medium Whole OHI scores of two and three.

The hypotheses that were set out to address the primary research questions were related to the distribution of bacterial attack amongst remains from different phases and the differences in patterns of bioerosion between bones from different Historical sites. The discussion of the variation in bacterial bioerosion will begin with a description of the primary factors that influenced the nature of bacterial tunnelling. The discussion will then move on to an examination of the differences in patterns of bacterial bioerosion between bones from different Historical sites. This strategy allowed for the hypotheses to be addressed directly.

7.1.1.2.1 Bacterial Bioerosion and Skeletal Element

It was important to establish whether bacterial bioerosion varied with skeletal element in order to confirm that all the samples could be included in the overall analysis. The majority (97%) of bone thin sections originated from the femur. The rest had been taken from various other long bones. There were no significant differences in levels of histological preservation between samples taken from different skeletal elements, either amongst the assemblage as a whole, or across single site assemblages. There were no consistent trends in bacterial bioerosion amongst particular skeletal elements. Bacterial bone bioerosion did not vary significantly with skeletal element within the remains sampled for the current study.

Long bones include similar ratios of cortical and trabecular bone (Junqueira *et al.* 1986). Variation in bacterial bone bioerosion with skeletal element has previously been explained by anatomy or microstructural organisation (Hanson & Buikstra 1987; Bell *et al.* 1996; Jans *et al.* 2004; Turner-Walker 2008). These previous studies included samples of long bones and non-long bones (Hanson & Buikstra 1987; Hedges 2002; Jans *et al.* 2004). Differences in levels of histological preservation amongst samples used in previous studies followed the division between long-bones and non-long bones. The lack of evidence from the Primary Analysis of the current study for variation in bacterial bone bioerosion with anatomy suggested that the variation in bacterial tunnelling with skeletal element is a result of differences in cortical/trabecular ratios or overall natural bone porosity.

The results from the histological analysis of the bones from Havnø shell midden were used to supplement the conclusions of the Primary Analysis regarding variation of bacterial bone bioerosion with skeletal element. The histological preservation of the Havnø human bone assemblage was not dependent upon skeletal element and there were no correlations between bacterial bone bioerosion and anatomical location. These results supported the conclusions from the Primary Analysis and inferred that bacterial bioerosion was not associated with anatomy, particularly a skeletal element's proximity to the gut. This conclusion was questionable to some extent, as anatomical area was crudely defined in the current study and unrecorded variables, such as bodily posture during initial decomposition, may have had some bearing on a bone's proximity to the source of putrefactive bacteria (Jans *et al.* 2004).

The cranial and metatarsal fragments sampled from Havnø represented those skeletal elements that would have lain farthest from the gut during putrefaction. These bone samples demonstrated variable levels of bacterial attack. The two phalanges scored the highest and

lowest possible Whole OHI scores and provided evidence that bones which are most remote from the internal organs can demonstrate extensive levels of bacterial bioerosion. This finding suggested that there was no limit to the extent a bone could be bioeroded based on its anatomical position.

The Havnø study sample mostly consisted of long bones and the results from this site was consistent with the suggestion that variation in bacterial bioerosion with skeletal element is dependent on ratios of cortical and trabecular bone. The small number of disparate skeletal elements that were sampled from Havnø and the high level of variation in their Whole OHI scores, meant that these results had only limited scope in establishing whether bacterial bioerosion could be expected to vary with skeletal element on a universal scale. The results from Havnø and the main assemblage provided no reason to exclude the small, but pertinent number of non-femoral thin sections used in the Primary Analysis. However, the small number of non-femoral samples that were included meant that this result could not be used to state definitively that bacterial bone bioerosion does not vary with skeletal element.

7.1.1.2.2 Bacterial Bioerosion and Age-at-Death

The variable that had the greatest influence on Whole OHI score and the presence of bacterial attack amongst the samples used in the current study was age-at-death. Turner-Walker (2008: 16) suggested that the dichotomy between articulated human bones and butchered animal bones used by Jans *et al.* (2004) to justify an enteric model of bacterial bone bioerosion was a product of age-related differences in microstructure having affected the logistics of exogenous microbial invasion. However, the relationship between age and bacterial bone bioerosion observed within the samples used in the current study did not conform to Turner-Walker's (2008: 16) model. Turner-Walker (2008: 16) suggested that the bones of younger individuals would be less susceptible to bacterial bone bioerosion because of their lower natural porosity. Neonatal samples demonstrated significantly higher Whole OHI scores compared to samples of older individuals. However, samples from bones of children demonstrated lower levels of histological preservation than those from juveniles. The median Whole OHI score of the juvenile remains was identical to that of the adults. The adult samples demonstrated a slightly elevated distribution of Whole OHI scores compared to the juvenile remains. There was no linear association between age-at-death and bacterial bone bioerosion, which refuted Turner-Walker's (2008: 16) explanation for differences in levels of bioerosion between articulated and

butchered archaeological remains (Jans *et al.* 2004). All variation in bacterial bioerosion related to age-at-death amongst the current study sample was explained by the differences between neonatal and post-neonatal bone.

The nature of the histological preservation of neonatal bones was refined by the results of the presence of bacterial bioerosion. Forty-nine per cent of neonatal bones from across all sites were free from bacterial bioerosion, which contrasted with 9% of post-neonatal samples. Neonatal age of an individual was the primary factor that dictated whether or not a bone had been bioeroded. There was no difference in the extent of bacterial bioerosion between neonatal and post-neonatal remains that had been bioeroded, which confirmed that higher distributions of Whole OHI scores amongst neonatal samples was not the result of variably elevated levels of histological preservation, but the high numbers of neonatal samples that remained free from bacterial bioerosion. High histological preservation of neonatal remains was observed consistently within isolated site assemblages. These results indicated that there was a factor intrinsic to the remains of infants less than one month old that prevented their bones from experiencing putrefactive bioerosion. This effect subsided once an infant lived past its first few weeks.

White's (2009) study of archaeological bone reported that neonatal remains were more often free from bacterial bioerosion. These findings were supported by similar results from the bones of experimentally-deposited pig carcasses (White 2009). The present study had expanded on a selection of archaeological bones that were used by White (2009) and so a similar result was expected. The present study confirmed White's (2009) results on a larger scale. White's (2009) research was mostly concerned with the histological analysis of neonatal bones and so the current study provided a broader contrast between neonatal and post-neonatal remains.

White (2009) argued that the best explanation for the lack of bacterial bioerosion within neonatal samples was the sterility of infant intestinal tracts at birth (Mackie 1999). Those infants that were stillborn or lived only a few days after birth would not have developed the enteric osteolytic bacteria responsible for the production of non-Wedl MFD (Mackie 1999; Jans *et al.* 2004; Nielsen-Marsh *et al.* 2007; White 2009). The binary preservation of the neonatal bones was consistent with the dichotomy between infants that had differentially lived long enough to develop colonies of gut microbiota responsible for bacterial bone bioerosion. This interpretation indicated that almost half of the neonatal samples used in the current study originated from individuals that were likely to have been stillborn.

There were no other intrinsic differences between neonatal and post-neonatal remains that could have provided an alternative explanation for the dichotomy in the presence of bacterial bioerosion. Neonatal bone is less mineralised than bone from more mature individuals (Junqueira *et al.* 1986). However, the mineral phase represents the bone fraction that bacteria struggle to break down (Hackett 1981; Bell *et al.* 1996; Hedges 2002; Turner-Walker 2008). Low mineralisation within neonatal bones would be expected to encourage bacterial attack, if it were to have any effect at all.

Neonatal bone has not been subjected to secondary remodelling and consequently contains fewer Haversian systems (Junqueira *et al.* 1986). The use of Haversian canals by invasive osteolytic bacteria suggests that the low numbers of secondary osteons might explain the lack of bacterial bioerosion within the neonatal samples (Turner-Walker 2012). However, secondary osteon density increases cumulatively with age and it would be expected that bacterial bioerosion would have increased progressively with age-at-death if the abundance of osteons were responsible for patterns of bacterial attack (Junqueira *et al.* 1986; Kerley 1965). Neonatal bone is vascularised to some extent, and so low numbers of osteons would not explain the absence of non-Wedl MFD from this category of samples.

Under a model where bacterial bioerosion is dictated by whether or not and individual was stillborn, it might be expected that younger foetal individuals would be more likely to demonstrate higher levels of histological preservation. However, it was decided that a test of this assertion would not be within the scope of this thesis. It was probable that a combination of imprecise or inaccurate osteological age estimations and the differential survival of premature infants would distort any changes to bacterial bone bioerosion that related to foetal age. One *in situ* foetal skeleton that was sampled from the Bantycock Roman cemetery demonstrated high levels of bacterial bioerosion. The bones of this infant may have been attacked by the enteric bacteria of the mother, whose skeleton had been extensively bioeroded.

The results from the neonatal individuals suggested that stillborn bodies do not undergo significant putrefaction. These bodies must decompose through sterile autolysis and exogenous decay (Polson *et al.* 1985). Circumvention of putrefaction is the primary mechanism that is used to promote preservation of the soft tissues and it is likely that neonatal bodies would be more prone to spontaneous mummification (Jansen 1984; Polson *et al.* 1985; Campobasso *et al.* 2001). Forensic studies have noted that neonatal putrefaction is often delayed or stunted (Jansen 1984; Polson *et al.* 1985; Campobasso *et al.* 2001). Anecdotal

forensic evidence has indicated that the bodies of stillborn or murdered new-born infants often mummify (Polson *et al.* 1985; Campobasso *et al.* 2001). This phenomenon is regularly attributed to the mummifying properties of the clandestine environments where infant bodies are often hidden, such as airing cupboards (Polson *et al.* 1985; Janaway 1996; Campobasso *et al.* 2001). However, the sterility of new-born infant intestinal tracts suggests that these bodies may be intrinsically more susceptible to mummification.

There have been no systematic studies that have compared the nature of decomposition within neonatal and non-neonatal remains. Experimental studies of pig carcasses have noted that neonatal bodies tend to skeletonise more quickly than adults (White 2009; Sutherland *et al.* 2013). However, the remains used in these examples were buried or sub-aerially exposed. In both scenarios the faster skeletonisation of the neonatal remains was probably attributable to their lower body mass, which would have ensured a shorter period of exogenous decay (Sutherland *et al.* 2013). A buried putrefying body influences the chemical properties of its surrounding environment through the release of heat, fluids and gases (Janaway 1996; Vass *et al.* 2002; Dent *et al.* 2004; Carter *et al.* 2007; Haslam & Tibbett 2009). These substances can be hostile towards the proliferation of exogenous soil bacteria (Janaway 1996; Dent *et al.* 2004; Carter *et al.* 2007). The absence of putrefaction might enable exogenous bacterial decay of buried neonatal bodies.

These results suggested that histological preservation of neonatal remains that were free from bacterial bioerosion could not be used to infer early *post mortem* treatment. However, the consistency in levels of bacterial attack within bioeroded neonatal and post-neonatal remains suggested that significant variation in bioeroded neonatal bones would require further explanation. The nature of the age-related variation in the presence of bacterial bioerosion was consistent with the putrefactive model of bacterial attack. The ability to identify the bones of stillborn infants, whilst not directly consistent with the aims of the current project, could be useful for archaeologists in attempting to identify mortuary environments that were reserved for stillborn infant deposition, such as unconsecrated Catholic cemeteries (Finlay 2000; Murphy 2008). Higher numbers of stillborn infants would be expected to be present within an unbaptised cohort of infant remains (Finlay 2000). Therefore, whilst assemblages from both consecrated and unconsecrated cemeteries might demonstrate variable levels of bioerosion, unbioeroded neonatal samples would be expected to appear more abundantly amongst the latter. A deficiency in the number of unbioeroded neonatal remains recovered from a cemetery would infer that stillborn and young infants had been deposited elsewhere.

7.1.1.2.3 Bacterial Bioerosion and Anoxia

The variable that demonstrated the next highest correlation with changes in Whole OHI score was recovery of a bone from an anoxic environment. Forty samples (13%) originated from skeletons that had been deposited within an anoxic environment. Bone recovered from these sediments demonstrated lower levels of bacterial bioerosion than those retrieved from aerobic conditions. The relationship between anoxic environments, putrefaction and bone bioerosion was discussed in earlier chapters and the correlation between histological preservation and anoxic environment was expected (Turner-Walker & Jans 2008; Hollund *et al.* 2012; Turner-Walker 2012). The distribution of Whole OHI scores amongst bone samples from the two waterlogged Historical sites, Carver Street and Coronation Street, were similarly elevated and variable. The two Later Prehistoric skeletons that had been recovered from anoxic environments were free from microbial bioerosion.

Most of the samples of bone from anoxic environments had been bioeroded by bacteria. Anoxic environments limited rather than prevented bacterial bone bioerosion, which was highlighted by the weaker association between an anoxic environment and the presence of bacterial attack. When the neonatal remains were removed from the distribution, 19% of bones from anoxic environments were free from microbial bioerosion. The results from the whole assemblage suggested that Later Prehistoric remains were more likely to have been subjected to processes that inhibited putrefactive bioerosion of bone. Phase had a larger effect on the presence of bacterial bioerosion than anoxic environment. When the Later Prehistoric bones were removed from the distributions, the number of remains from anoxic deposits that were free from bacterial bioerosion dropped to 14%. Anoxic environments promoted lower levels of bacterial bioerosion, but only occasionally inhibited microbial destruction. This result was probably a consequence of environmental anoxia having been caused by intermittent waterlogging.

The anoxic-deposited Roman remains from Castricum studied by Hollund *et al.* (2012) were mostly free from microbial bioerosion. All of these remains had been deposited directly into sediments that were intrinsically anoxic (Hollund *et al.* 2012). Burial contexts that lie close to, but not within the capillary zone of the water table, would only experience periodic anoxia relating to seasonal waterlogging (Janaway 1996; Björdel *et al.* 2000; Turner-Walker & Jans 2008). Sk. 853 from Bradley Fen had been deposited in an environment that would have been permanently waterlogged throughout the duration of decomposition (Knight 20008, personal

communication). The thin sections from this skeleton were free from microbial bioerosion. The perseverance of organic grave goods within the cist of the Langwell Farm skeleton indicated that this environment had also been waterlogged soon after deposition (Lelong 2011). The Langwell skeleton also yielded a sample that was free from microbial attack.

The skeletons from Coronation Street and Carver Street were interred at variable depths at different times of the year around or within the capillary zone of the water table (ARCUS 2004; Oxford Archaeology North 2008). The variation in the distribution of Whole OHI scores amongst these remains was likely to be related to how far bodily decomposition had progressed before each grave had become inundated (Hollund *et al.* 2012). The consistency in measures of bacterial bioerosion between remains from these two assemblages suggested that the intermittent waterlogging had produced similar patterns of putrefactive bioerosion. These results suggested that there may be a particular generalised patterning of Whole OHI scores consistent with remains obtained from an intermittently-waterlogged cemetery.

Skeletons excavated from the same areas of a cemetery or from similar burial depths would have been equally susceptible to seasonal waterlogging and would be expected to demonstrate comparable patterns of bacterial bone bioerosion. It was impossible to test this assertion within both the Coronation Street and Carver Street assemblages. All Coronation Street samples had been taken from disarticulated charnel. The site report for Carver Street had recorded the relative positions of skeletons within each grave (ARCUS 2004). These diagrams provided stratigraphic relationships between skeletons from the same grave, but there was no way to calculate the absolute or relative depth of each interment. No two skeletons had been sampled from the same grave. The effect of increased burial depth on putrefaction could be observed within the deepest-buried skeletons from Carver Street, Sk 1093 and 1114, which demonstrated high levels of soft tissue preservation (ARCUS 2004). Unfortunately, neither of these skeletons had been sampled for thin section analysis.

All bones from Carver Street that demonstrated the highest levels of histological preservation originated from graves within a single row, Row 6 (ARCUS 2004). The spatial specificity of bacterial bone bioerosion suggested that the position of these graves had rendered their occupants more prone to specific environmental conditions that interfered with bodily putrefaction. However, the remains that demonstrated high levels of soft tissue preservation had not been recovered from this row, which suggested that burial depth was just as important as horizontal position in controlling soft tissue decomposition relating to waterlogging. One possible explanation for the spatial specificity of histological preservation

was that the graves within Row 6 were deeper than the rest. An alternative explanation may be that this particular row of graves had been produced within a similar time frame, when the water level was high enough to inhibit bodily putrefaction. This point could be tested through analysis of the burial records for Carver Street, although there was no scope for this search to have been undertaken as part of the present study.

These results were consistent with the association between bacterial bioerosion and putrefaction, but suggested that the histological preservation of bones from anoxic environments cannot be used to infer early taphonomic treatment beyond the level of bodily decomposition that had taken place before the burial environment had been rendered anoxic (Hollund *et al.* 2012). Elevated patterns of bacterial bone bioerosion within archaeological assemblages from anoxic conditions, such as those observed amongst the remains from Carver Street and Coronation Street, may be used to infer whether particular burial environments were likely to have been anoxic, or subject to varying cycles of anoxia, during the decomposition of the interred bodies.

7.1.1.2.4 Bacterial Bioerosion and Black Death

The variable that had the next largest effect on the distribution of Whole OHI scores, but not the presence of bacterial bioerosion, was whether or not a bone originated from a Black Death grave. Bones from Black Death graves demonstrated elevated and more variable distributions of Whole OHI scores than those from all other contexts, after the neonatal and anoxic-deposited samples were excluded. The same factor had not influenced the presence of bacterial bioerosion, which suggested that the underlying factor responsible for this effect reduced rather than obstructed bone exposure to putrefaction.

Evidence for slumping of the soils and skeletal disarticulation within the Black Death graves had indicated that there had been a delay between death and burial in some instances, which suggested that these remains had decomposed to some extent before they were buried (Grainger *et al.* 2008: 19). Delays may have resulted from the high volume of bodies that required burial, failure to collect bodies directly after death or transportation of bodies to the site from surrounding parishes (Grainger *et al.* 2008). A delay between death and burial would explain the variable and elevated levels of histological preservation amongst the Black Death bones. Unburied bodies would have been rapidly skeletonised by insects, thereby reducing the

levels of soft tissue putrefaction the bones experienced once the remains were buried (Simmons *et al.* 2010). The extent of bacterial bone bioerosion would be dependent on how far the body had decomposed above ground. The lack of correlation between Black Death bones and the presence of bacterial bioerosion was consistent with this interpretation. If a body skeletonises entirely on the ground surface, the rapid loss of soft tissue can prevent the formation of non-Wedl MFD (Rodriguez & Bass 1983; 1985; Bell *et al.* 1996; Turner-Walker & Jans 2008; Fernández-Jalvo *et al.* 2010; Simmons *et al.* 2010). There was no evidence from levels of disarticulation that any of the Black Death remains had entirely skeletonised above ground and so all of these skeletons would have experienced some level of putrefactive attack (Grainger *et al.* 2008).

A possible alternative scenario was that pathological bacteria associated with the Plague variably accelerated skeletonisation within the Black Death samples and reduced the levels of putrefactive activity that the bones experienced (Campobasso *et al.* 2001; Vass 2011; Zhou & Bayard 2011; Fereira & Cunha 2013). Side-effects of the disease may have reduced the microbial load of the gut and the severity of putrefactive bacterial attack (Vass 2011; Zhou & Bayard 2011; Fereira & Cunha 2013). Loss of body mass from emaciation could have also reduced the duration of skeletonisation (Mant 1987; Zhou & Bayard 2011; Fereira & Cunha 2013). Variability in bacterial bone bioerosion observed amongst the Black Death samples would have been influenced by the extent to which each case of Plague had affected these factors.

The uniformity of Whole OHI scores amongst the rest of the Historical assemblage, which would have inevitably included individuals that died of infectious disease, suggested that pathological conditions had little effect on bacterial bone bioerosion. The association between rates of skeletonisation and burial or sub-aerial exposure is well-established within the forensic literature, whereas the correspondence between infectious disease and decomposition is more ambiguous (Mann *et al.* 1990; Vass 2011; Fereira & Cunha 2013). The differential treatment of a proportion of the Black Death remains was most likely to account for their significantly variable levels of bacterial bone bioerosion (Rodriguez & Bass 1983; 1985; Simmons *et al.* 2010). Significant variation in Whole OHI score within samples of bone from Black Death contexts provided the first hints towards a relationship between bacterial bioerosion and early *post mortem* treatment.

7.1.1.2.5 Bacterial Bioerosion and Archaeological Phase

The final variable that had a significant effect on the presence and extent of bacterial bioerosion was archaeological phase. When the neonatal, anoxic-deposited and Black Death remains were excluded, 208 samples remained, which represented 69% of the original study sample. The difference in bacterial bioerosion amongst these remaining samples was dictated by whether they originated from a Historical or Later Prehistoric context. This variable was the last to significantly influence measures of bacterial bioerosion. Archaeological phase controlled the presence of bacterial bioerosion to a greater extent than the presence of an anoxic burial environment or Black Death context. The relationship between bacterial bioerosion and phase directly supported the third hypothesis formulated in the Background chapter (page 98) relating to the validity of the relationship between bacterial bioerosion and funerary treatment. The assumptions regarding the use of the Later Prehistoric/Historical division as a proxy of funerary treatment suggested that levels of bacterial bioerosion within post-neonatal remains that had not been recovered from anoxic environments were likely to reflect differential exposure to putrefaction encouraged by funerary processes.

The majority of remains from the Historical assemblage demonstrated high levels of bacterial bioerosion. The distribution of Whole OHI scores amongst the Later Prehistoric samples was elevated and more variable than the distribution amongst the Historical samples. The modal and median OHI scores of the Historical remains were both zero, and the subsequent distribution resembled a half-normal curve. The modal Whole OHI score within the Later Prehistoric assemblage was also zero, but the median equalled one and significant peaks were present at scores of two and five. These peaks were what differentiated the Later Prehistoric distribution from that of the Historical assemblage. Bones from Later Prehistoric contexts were significantly more likely to have remained free from bacterial bone bioerosion than those obtained from Historical sites.

The notion that funerary rite was the causal factor behind the different levels of bacterial bioerosion amongst the Historical and Later Prehistoric remains was supported by the nature of the difference between these sample sets when compared to models of bodily decomposition established by forensic and experimental studies. It had been predicted that bones from Historical sites would demonstrate high levels of bacterial bioerosion, as it could be assumed that the majority of these samples had been exposed to extensive putrefaction through burial soon after death (Rodriguez & Bass 1983; 1985; Jans *et al.* 2004). The

interquartile range of the Historical distribution was confined to the lowest OHI scores of zero and one, representing the most severe levels of bacterial destruction.

It had been predicted that if bacterial bioerosion related to funerary treatment, the Later Prehistoric bones would demonstrate more variable patterns of internal bone bioerosion as there was evidence that these bodies had been treated diversely. Burial was likely to promote the highest levels of putrefactive bone bioerosion and so Whole OHI score within an assemblage that had been subjected to variable treatment could only be elevated compared to the Historical samples (Rodriguez & Bass 1983; 1985; Manhein 1997; Rodriguez 1997; Campobasso *et al.* 2001; Jans *et al.* 2004; Nielsen-Marsh *et al.* 2007; Vass 2011). The higher median value and broad interquartile range of the Later Prehistoric Whole OHI distribution suggested that histological preservation amongst this assemblage was elevated and variable compared to the Historical study sample. Bacterial bioerosion of the archaeological samples used in the current study varied predictably based on knowledge regarding variable processes of decomposition and known treatment of the dead.

7.1.1.2.6 Uniformity in Historical OHI scores

The requirements of the first two hypotheses put forward in the Background chapter (page 98) were that the distribution of Whole OHI scores amongst the Historical remains would form a half-normal shape, and that there would be no difference in measures of bacterial bioerosion between bones from different Historical site assemblages. It had been predicted that neonatal and anoxic-deposited remains were likely to increase overall levels of histological preservation amongst the Historical samples and therefore the exclusion of these types of sample was considered to be valid. The exclusion of the Black Death samples was also valid, as there was prior evidence that these remains had not been interred immediately after death and could not be considered as part of the consistently-buried Historical cohort of remains. The Historical assemblage that was left after the exclusion of these samples (the Historical baseline) represented the group of skeletons that were buried soon after death, subjected to high levels of putrefactive bioerosion and were expected to demonstrate the consistent patterns of extensive bacterial attack detailed within the first and second hypotheses.

The distribution of Whole OHI score amongst the Historical baseline assemblage was significantly different from a half-normal model. Ostensibly, this result refuted the

expectations of the first hypothesis that distribution of Whole OHI scores amongst the Historical assemblage would form a half-normal shape. However, further analysis revealed that the Historical baseline distribution deviated from the half-normal model in terms of its significant leptokurtic shape. A leptokurtic distribution is produced when data points closely cluster around the mean, which in a normal distribution is also usually the modal value. This distribution is symptomatic of low variation around the modal value. The Historical baseline distribution was significantly less variable than a normal distribution around Whole OHI scores of zero. The normal distribution had been chosen as the comparative model because it represented natural variation within a continuous variable that could be explained by chance. Therefore, although the Historical baseline distribution of Whole OHI scores was not consistent with the statistical criteria of the first hypothesis, the significantly low variance of this distribution around zero was more consistent with the specific hypothesis that Historical remains would demonstrate invariably poor levels of histological preservation. Failure to fulfil the statistical criteria of the first hypothesis was attributable to a weakness within the predictive model in not recognising that the hypothesis would still be acceptable if variation within the Historical assemblage was significantly lower than what might be expected as a result random chance. Histological preservation within the Historical baseline assemblage was invariably poor and consistent with levels of putrefaction that would be experienced by bones from bodies that were buried immediately after death.

Ninety-eight-per-cent of the Historical baseline sample had been bioeroded by bacteria. This finding combined with the variability in Whole OHI scores meant that the two samples from this distribution that were free from bacterial bioerosion represented anomalous outliers. One of these samples had been taken from the Bolsover charnel assemblage. Evidence for specific environmental or taphonomic factors that may have been responsible for this sample's anomalous histological preservation were not forthcoming. The other sample originated from the Royal Mint skeleton that had been forced into a coffin that was too small for the body and covered with slaked lime (Grainger & Phillpotts 2011: 104). The circumstances of this skeleton had suggested to the excavators that it belonged to a high status individual whose body had been displayed before burial (Grainger & Phillpotts 2011: 104). The body may have been treated with lime to arrest decomposition and ensure that it looked presentable when it was displayed (Grainger & Phillpotts 2011: 104). Experiments that have investigated the effects of liming on the decomposition of pig carcasses found that it interferes with decomposition within the first six months of burial (Schotsmans *et al.* 2012). The presence of lime within the burial environment has been implicated in the survival of soft tissue within numerous other

burials (Aufderheide 2003; Kim *et al.* 2008). Lime is bactericidal, but can also preserve soft tissue through desiccation (Aufderheide 2003; Schotsmans *et al.* 2012). It was likely that the absence of bacterial attack from the limed Royal Mint skeleton sample was attributable to liming having interfered with bodily putrefaction. This specimen provides further evidence for the association between bacterial bioerosion and funerary treatment.

The second expectation with regards to the relationship between bacterial bioerosion and funerary treatment was that distributions of Whole OHI scores would be similar between different Historical site assemblages. There was no statistically significant difference in Whole OHI scores and the presence of bacterial attack between bone samples from different sites within the Historical baseline assemblage. When combined with the results from this assemblage as a whole, this finding indicated that the histological preservation of all Historical site assemblages was invariably poor. These two findings were consistent with the first two hypotheses and suggested that levels of bacterial bioerosion conformed to what would be expected within skeletons from bodies that were buried soon after death. All significant variation in bacterial bioerosion of Historical samples away from this consistent diagenetic signature of inhumation could be attributed to the influence of neonatal, anoxic-deposited and Black Death samples.

7.1.1.2.7 Uninfluential Factors

Significant variation in bacterial bioerosion amongst the Historical remains was explained by neonatal, anoxic-deposited and Black Death remains. The dichotomy between the Historical and Later Prehistoric assemblages had been taken as a proxy of differential funerary treatment, which could not be measured directly. The use of this proxy was risky, as there were a number of factors that differed between Later Prehistoric and Historical remains that might have affected the way the bodies had decomposed. However, all factors that had been recorded as having potentially affected bacterial bone bioerosion were controlled to some extent or showed no significant relationship with Whole OHI score or the presence of bacterial tunnelling. These variables could not have been responsible for the excess variation in bacterial bioerosion within the Later Prehistoric samples.

Age-at-death (excluding neonatal bone), sex and skeletal element all demonstrated no association with measures of bacterial bioerosion, which refuted the possibility that

demographic differences in bone microstructure were responsible for patterns of bacterial attack (Jans *et al.* 2004; Turner-Walker 2008). The nature of the burial soil that surrounded bone samples also had no influence on bacterial bioerosion. This result was particularly pertinent to the underlying assumptions of the endogenous origin of osteolytic bacteria, particularly when it was considered that the bones from Carsington Pasture Cave had not been buried yet demonstrated extensive levels of bacterial bioerosion. Retrieval of bones from the open environment of Carsington Pasture Cave had no influential effect on the presence or extent of bacterial bioerosion and therefore it was unlikely that non-Wedl MFD had been produced by exogenous soil bacteria. The categories of soil type were problematic, but in general the lack of association between measures of bacterial bioerosion and burial soil further supported the assumption that bacterial bioerosion was produced by enteric bacteria rather than exogenous soil bacteria. This result also suggested that beyond anoxic environments, variation in qualities of the burial sediment had not affected bodily decomposition in a way that impacted on putrefactive bioerosion of bone.

The lack of variation in measures of bacterial bone bioerosion amongst the Historical remains suggested that unrecorded or non-recordable factors were unlikely to have affected bodily putrefaction in a way that influenced bacterial bone bioerosion. It was important to make a note of these factors to discount their potential influence on the variation in bacterial bioerosion amongst the Later Prehistoric samples. There was evidence that the remains from the majority of Historical sites had been differentially subjected to coffin burial (Foster 1992; Boyle *et al.* 1995; ARCUS 2004; Grainger *et al.* 2008; Gibson *et al.* 2009; Nolan *et al.* 2010). The sporadic survival of coffin furniture into the archaeological record meant that it was impossible to accurately record the occurrence of coffined remains amongst the study sample. However if coffin burial had interfered with putrefactive bone bioerosion, measures of bacterial attack between and within bones from Historical sites would have been highly variable. The site-specific results from the Royal Mint assemblage suggested that there was no association between coffin burial and bacterial bone bioerosion (Grainger *et al.* 2008). The results from the Royal Mint assemblage also suggested that deposition within a single or mass grave also had no effect on levels of bacterial bioerosion. This result was expected given that an individual's gut bacteria are capable of extensively bioeroding the skeleton by themselves without any assistance from any extraneous gut bacteria present within the surrounding environment (Janaway 1996; Hedges 2002; Jans *et al.* 2004).

A similar logic could be applied to the effects of the presence of clothing and wrappings. There were variable osteological and artefactual indications for the presence of tight wrappings or

clothing at each Historical site (Boulter 1992; Foster 1992; Boyle *et al.* 1995; ARCUS 2004; Grainger *et al.* 2008; Gibson *et al.* 2009; McIntyre & Bruce 2010). The temporal variation in the Historical remains sampled for this study, sometimes over single sites, meant that a certain number of individuals from each Historical cemetery would have been variably clothed or wrapped (Foster 1992; Gibson *et al.* 2009). The lack of unexplained variation in bacterial bioerosion amongst Historical samples suggested that clothing and wrappings had not substantially affected exposure to putrefactive bacterial attack.

It was unlikely that all of the Historical burials were interred at the same time of year. The lack of variation in bacterial bioerosion amongst the Historical remains suggested that season of burial had not significantly affected levels of putrefactive bone bioerosion. These results were consistent with those obtained from the microscopic study of bones from fallen livestock conducted by Fernández-Jalvo *et al.* (2010). The results from the current study indicated that whilst seasonal changes often alter the rate of decomposition within buried remains, the levels of putrefaction that a bone experienced does not change significantly (Rodriguez & Bass 1983; Mant 1987; Mann *et al.* 1990; Manhein 1997; Bass 1997; Wilson *et al.* 2007; Fernández-Jalvo *et al.* 2010; Meyer *et al.* 2013). Seasonality was likely to have affected putrefactive bone bioerosion indirectly at sites where it promoted waterlogging. The consistency in bacterial bioerosion amongst the Historical remains indicated that climatic changes over time had not significantly impacted bacterial bone bioerosion. It was difficult to determine whether this finding had similar implications for the results from the Later Prehistoric remains, which represented a longer duration of time that included larger climatic fluctuations (Darvill 2010).

Burial depth varied between and within remains recovered from different Historical sites (Boulter 1992; Foster 1992; Boyle *et al.* 1995; ARCUS 2004; Grainger *et al.* 2008; Gibson *et al.* 2009; McIntyre & Bruce 2010). The consistency of bacterial bioerosion within the Historical remains suggested that burial depth had not dictated levels of putrefactive bioerosion unless it had resulted in the body being placed within an anoxic environment (ARCUS 2004; Gibson *et al.* 2009; Hollund *et al.* 2012). It was still possible that particularly deep burials curtail putrefaction and bone bioerosion through their intrinsic anoxia (ARCUS 2004; Dent *et al.* 2004; Gibson *et al.* 2009). This possibility could not be assessed within the current study sample, as all bones that had been subjected to deep burial had also been waterlogged (ARCUS 2004; Gibson *et al.* 2009). These results suggested that although variations in moderate burial depths can affect the rate of bodily decomposition, they do not alter the overall level of putrefaction that bones experience (Campobasso *et al.* 2001).

The consistency in Whole OHI score amongst the Historical remains suggested that factors intrinsic to an individual that could have affected gut bacteria, such as diet, disease, microbiome health and composition, had not significantly influenced putrefactive bacterial bioerosion of bone. These factors would have varied within and between the temporally diverse populations that constituted the Historical study sample. This result indicated that the species of bacteria responsible for the production of non-Wedl MFD occur commonly within most human populations through time and that their presence and ability to bioerode bone is not affected by diet. Forensic studies have indicated that decomposition is accelerated within individuals who died of infectious diseases. The lack of variation in bacterial bioerosion amongst the Historical population, some of which were likely to have died of infectious conditions, suggested that these diseases had not substantially altered the extent of putrefactive bone bioerosion (Campobasso *et al.* 2001; Vass 2011; Fereira & Cunha 2013). This general conclusion was supported by the specific finding that there was no significant difference in levels of bacterial bioerosion between leprotic and healthy skeletal samples from the medieval St. Leonard Hospital cemetery in Grantham.

Penetrative trauma represented another variable that was likely to have varied between and within the Historical assemblages (Boulter 1992; Foster 1992; Boyle *et al.* 1995; ARCUS 2004; Grainger *et al.* 2008; Gibson *et al.* 2009; McIntyre & Bruce 2010). The results of investigations into the effects of penetrative trauma on decomposition are variable, although some studies have suggested that it accelerates skeletonisation (Micozzi 1986; Mant 1987; Galloway *et al.* 1989; Mann *et al.* 1990; Cross & Simmons 2010). The Historical consistency in bacterial bone bioerosion indicated that penetrative trauma had little effect on the levels of putrefactive bioerosion that bones experienced. However, it was possible that only small numbers of the remains sampled had been subject to penetrative trauma, in which case variation in bacterial bioerosion attributable to this factor may have failed to impact on overall diagenetic trends. Penetrative trauma may represent another factor that affected the rate, but not the extent of putrefactive decomposition experienced by a bone. Alterations in the rate of bodily decomposition attributable to penetrative trauma may be localised to affected areas.

The results from the samples included in the current study may be surprising given that some uninfluential variables are commonly cited as primary influences on cadaveric decomposition (Rodriguez & Bass 1983; 1985; Janaway 1996; Campobasso *et al.* 2001; Vass 2011). The common feature of many of these non-influential factors was that they affect the rate of decomposition, rather than the overall level of putrefaction experienced by the bones (Rodriguez & Bass 1983; 1985; Janaway 1996; Campobasso *et al.* 2001; Vass 2011). These

results were consistent with the hypothesis that only factors that sufficiently reduce the level of putrefaction experienced by a bone, such as rapid soft tissue loss by extraneous means, will affect bacterial bone bioerosion (Jans *et al.* 2004; Nielsen-Marsh *et al.* 2007). This finding indicated that anthropogenic processes such as coffin burial will not produce a characteristic signature of bacterial bone bioerosion. However, the low impact of these processes on bacterial bone bioerosion would ensure that it would be easier to discern diagenetic signatures of more effective treatments.

7.1.1.2.8 Later Prehistoric Assemblage

When the neonatal (three samples from two sites) and anoxic-deposited (two samples from twos sites) remains were excluded from the distribution, the pattern of Whole OHI scores amongst the Later Prehistoric bones did not change substantially. The distribution was significantly different from a normal model. The modal value of this Later Prehistoric distribution was zero, but there were two secondary peaks at Whole OHI scores of two and five. The slightly platykurtic distribution of Later Prehistoric Whole OHI scores emphasised that the difference between this distribution and the Historical baseline was the higher levels of variation within the former. There was no significant difference in Whole OHI score or the presence of bacterial attack between Later Prehistoric site assemblages, although the results from both parameters were close to the significance threshold within the Holm-Bonferroni method (Appendix 2). Low sample sizes and high levels of variation in bacterial bioerosion across Later Prehistoric site assemblages could have affected statistical significance.

It was possible that unrecorded, unknown factors specific to the Later Prehistoric periods had produced the variation within this assemblage. However, it was difficult to determine what unrecorded variable could have influenced variation in the bacterial bioerosion within the Later Prehistoric assemblage without it having had some effect on the histological preservation of the Historical samples. Based on current knowledge regarding the relationship between taphonomy, putrefaction and bacterial bioerosion, funerary treatment represented the best explanation for the dichotomy in histological preservation observed between the Later Prehistoric and Historical sample assemblages. The next section presents attempts to account for the variation in bacterial bone bioerosion amongst the Later Prehistoric remains to explore whether there was any further evidential justification for the relationship between bacterial bioerosion and funerary treatment.

7.1.1.2.8.1 Remains from Cave Environments

All of the bones sampled that had been recovered from cave sites were disarticulated at the point of recovery. It could not be stated with absolute certainty that all individuals represented had decomposed within a cave. However, taphonomic analysis of the human bone assemblages from both cave sites suggested that most individuals were originally deposited as whole corpses (Chamberlain 1999; Papakonstantinou 2009). Therefore, it was assumed that the remains from cave sites had decomposed within these contexts from the outset and that patterns of bacterial bioerosion would reflect this process.

Patterns of cadaveric decomposition observed within caves indicated that cave deposition would result in bones being exposed to variably high levels of putrefactive bioerosion (Terrell-Nield & MacDonald 1997). The lack of significant difference in measures of bacterial bioerosion between cave-deposited remains and the variably-bioeroded Later Prehistoric assemblage suggested that the cave-deposited samples had been bioeroded diversely. Whole OHI scores amongst samples of post-neonatal bones from cave sites (Carsington Pasture Cave and Beeston Tor CX) were generally low, but slightly elevated and variable when compared to the Historical baseline. The higher histological preservation of the cave-deposited samples was partly attributable to the presence of bones that had been subjected to early *post mortem* manipulation (Chamberlain 1999; Jans *et al.* 2004; Nielsen-Marsh *et al.* 2007; Papakonstantinou 2009). The samples of bone from the Carsington Pasture Cave that demonstrated cut-marls indicative of dismemberment was free from microbial bioerosion. The association between cut-marks and histological preservation supported the hypothesis that bacterial bioerosion of bone is primarily controlled by interventions which would have neutralised the effect of putrefactive gut bacteria within the immediate *post mortem* period (Jans *et al.* 2004; Nielsen-Marsh *et al.* 2007).

Patterns of bacterial bioerosion within the cave-deposited post-neonatal bones that showed no evidence for dismemberment was still slightly elevated compared to the Historical baseline. Whole OHI scores of two were particularly well-represented amongst these samples. This patterning was consistent with what would be expected based on models of cadaveric decomposition in caves and indoor environments (Galloway *et al.* 1989; Goff 1991; Terrell-Nield & MacDonald 1997; Anderson 2011). The cave would have restricted insect interaction with the deposited corpses, promoting prolonged putrefaction (Galloway *et al.* 1989; Goff 1991; Terrell-Nield & MacDonald 1997; Anderson 2011; Vass *et al.* 2011). However, the small

loss of soft tissue promoted by insects could have been enough to have variably limited levels of putrefactive bioerosion experienced by the skeleton, which would have produced a diagenetic signature that was in-between those produced by burial and sub-aerial exposure. Therefore some of the deviant variation (Whole OHI scores of two and five) in bacterial bioerosion of the Later Prehistoric samples was attributable to Neolithic deposition of corpses within caves as well as dismemberment practices.

7.1.1.2.8.2 State of Articulation & Phase

The only variable that came close to exerting a significant influence on measures of bacterial bioerosion and explaining some of the variation in histological preservation amongst the Later Prehistoric remains was specific Later Prehistoric phase, Neolithic, Bronze Age or Iron Age. It had been predicted in the Methodology that if bacterial bioerosion related to funerary treatment it might be expected to vary with specific Later Prehistoric phase because of the culturally-specific changes in funerary treatment associated with different time periods (Bradley & Hodder 1979; Rowley-Conwy 2007). The use of archaeological phase (Later Prehistoric versus Historical) as a proxy for funerary treatment formed the basis of the current study. However the association between funerary treatment and Later Prehistoric phase was more tenuous than within the Later Prehistoric/Historical dichotomy, as less is known about the rites that were practised in the Later Prehistoric periods and how they varied with time and geography (Darvill 2010). Archaeological phases are artificial constructs and funerary ritual is not likely to transition neatly between each phase in all parts of the country (Bradley & Hodder 1979; Rowley-Conwy 2007; Darvill 2010). These observations suggested that any phase-specific variation in bacterial bioerosion amongst the Later Prehistoric remains was not likely to be straightforward. The lack of significant associations between bacterial bioerosion and Later Prehistoric phase was likely to be a product of these inconsistencies.

State of articulation represented an archaeological end-point that must have been related to how Later Prehistoric human remains had been treated after death. Immediate burial was assumed to represent the primary way of ensuring that an articulated skeleton survived into the archaeological record. It was expected that measures of putrefactive bioerosion would be similar between articulated Historical and Later Prehistoric assemblages. Various funerary processes can promote skeletal disarticulation, and so it was expected that the majority of variation in bacterial bone bioerosion amongst the Later Prehistoric samples would have

originated within the disarticulated bone samples. However, state of articulation had no significant influence on measures of bacterial bioerosion.

The distributions of bacterial bone bioerosion amongst the disarticulated Later Prehistoric remains met the expectations set out in the Methodology. Bacterial bioerosion was highly variable and differed from what was observed within the Historical baseline assemblage. The confirmation of the three Hypotheses regarding the relationship between bacterial bioerosion and funerary treatment suggested that variation within the disarticulated Later Prehistoric remains most likely corresponded with funerary treatments that had exposed the bone to diverse levels of putrefaction (Rodriguez & Bass 1983; 1985; Bell *et al.* 1996; Jans *et al.* 2004; Nielsen-Marsh *et al.* 2007; Simmons *et al.* 2010). The lack of correlation in measures of putrefactive bioerosion between Later Prehistoric remains recovered in different states of articulation related to the assumption that immediate burial is the primary way of ensuring that an articulated skeleton persists into the archaeological record.

It was thought that variation in bacterial bioerosion amongst the Later Prehistoric disarticulated assemblage might be explained by specific Later Prehistoric phase. The pattern of Whole OHI scores amongst the disarticulated assemblage was similar to the pattern amongst the samples as a whole. The majority of disarticulated samples had been allocated Whole OHI scores of zero, but secondary peaks were present at scores of two and five. Distributions of Whole OHI scores amongst samples from different phases was relatively constant. However, subtle variation in phase-specific distributions of bacterial bioerosion accounted for the primary differences between the disarticulated assemblage and the Historical baseline model.

Neolithic disarticulated samples constituted parts of the peaks at Whole OHI scores of two and five. At least one of these samples that had been allocated a Whole OHI score of five had been taken from a bone of a dismembered body. Another of these samples was from the Ingleby Barwick Bronze Age bone that had been erroneously attributed a Neolithic date. As discussed above, bones of Neolithic bodies that had decomposed within caves were responsible for the Neolithic representation of scores of two. Evidence for differential treatment of Neolithic remains and associated change in levels of bacterial bioerosion supported the link between bacterial bone bioerosion and funerary treatment but highlighted how variation in treatment might distort Later Prehistoric phase-specific patterns. The peak at Whole OHI score of five amongst the disarticulated Later Prehistoric assemblage mostly consisted of Bronze Age samples, whereas Iron Age samples contributed substantially to the peak at scores of two.

The distribution of Whole OHI scores amongst the articulated Later Prehistoric remains was similar to that observed amongst the disarticulated samples. Secondary peaks at Whole OHI scores of two and five were responsible for the deviation of this distribution from the Historical baseline. There were clearer divisions in Whole OHI score based on specific Later Prehistoric phase. All of the articulated Neolithic and Iron Age remains had been bioeroded. Distributions of Whole OHI scores amongst these samples were responsible for the peak at Whole OHI scores of two. These samples demonstrated a slightly elevated histological preservation compared to the Historical baseline, but in general their diagenetic signatures were consistent with the notion that articulated remains were protected from rapid soft tissue loss in the early *post mortem* period and their bones were subsequently exposed to high levels of putrefactive bioerosion. The only articulated Later Prehistoric bone samples that demonstrated high levels of histological preservation had been recovered from Bronze Age sites. It was these Bronze Age remains that constituted the main deviation of the Later Prehistoric articulated distribution away from the Historical baseline and what would be expected within bones from bodies that had been buried immediately after death. The high proportions of Bronze Age samples that were free from bacterial bioerosion were responsible for the close-to-significant variation in the presence of bacterial bioerosion amongst Later Prehistoric remains from different phases.

It was possible that the high proportions of unbioeroded samples of articulated Bronze Age bones may have occurred through the influence of one site that included larger numbers of such remains and had biased overall patterns. However, four out of the six Bronze Age sites that did not include anoxic deposits demonstrated high proportions of articulated bones that had not been bioeroded by bacteria. Sample sizes within some of the Bronze Age sites were low, however the rarity of unbioeroded bones from the Historical baseline distribution suggested that the occurrence of histologically well-preserved bones from articulated skeletons at multiple Bronze Age sites represented a real phase-specific phenomenon.

The variable extent of bacterial attack within disarticulated and articulated Later Prehistoric remains was very similar. Variation in bacterial attack amongst these assemblages was explained by subtle disparities attributable to a combination of phase and state of articulation. Trends were complex, which was likely to be attributable to the variable treatment of human remains throughout Later Prehistoric phases, as exemplified within the Neolithic cave-deposited samples. Remains from all Later Prehistoric phases contributed to the prominent peaks at Whole OHI scores of zero. A combination of Iron Age and Neolithic bones were mostly responsible for the secondary peak at Whole OHI scores of two. A combination of Neolithic

disarticulated bones and Bronze Age articulated and disarticulated samples were responsible for the higher Whole OHI scores of four and five.

Associations between chronology and bacterial bioerosion were also observed within samples from certain Later Prehistoric site assemblages. For instance, the Early Bronze Age specimens from Ingleby Barwick were free from bacterial bioerosion, whilst the Middle Bronze Age remains were filled with bacterial tunnelling (Annis *et al.* 1997). More subtle phase-specific variations in bone bioerosion were observed within Later Prehistoric remains from Neat's Court, Frälsegården, Cnip Headland, Carsington Pasture Cave, Cladh Hallan and South Dumpton Down. These patterns are discussed in more detail within the next chapter.

Phase-specific differences in measures of bacterial bone bioerosion could raise concerns about whether the archaeological age of remains had any bearing on bioerosion. Bacterial bioerosion linked to chronology would be more consistent with an exogenous origin for osteolytic bacteria. Previous studies of bone diagenesis in archaeological remains have consistently found no relationship between chronological age and bacterial bone bioerosion (Hedges *et al.* 1995; Hedges 2002). It would be expected that differences in bacterial bioerosion dictated by chronology would produce progressive patterns. Either levels of bacterial bioerosion would increase with age of remains because of the increased opportunities for bacterial exploitation, or they would decrease because of the greater potential for histologically well-preserved bones to survive into the archaeological record (Hedges 2002; Trueman & Martill 2002). Patterns of bacterial bioerosion within remains from different Later Prehistoric phases did not fit either of these models. Histological preservation was low within the Neolithic remains, increased into the Bronze Age then decreased within bones from the Iron Age. The high levels of histological preservation observed within the samples of bone from the Mesolithic/Early Neolithic Havnø site also deviated from a chronological model. This evidence was compounded by the observation that bacterial bioerosion varied considerably within samples of bones that dated to similar periods as well as within assemblages retrieved from the same site. The results of the current study agreed with previous research in indicating that chronological age has no bearing on bacterial bone bioerosion over archaeological timescales (Hedges *et al.* 1995; Hedges 2002).

Cultural change associated with specific phases is often thought to be associated with adaptation to climatic shifts (Bradley & Hodder 1979; Rowley-Conwy 2007; Darvill 2010). It was possible that differences in bacterial bioerosion with Later Prehistoric phase were attributable to shifts in climatic conditions that accompanied or even drove the cultural change whilst also

altering the nature of cadaveric decomposition. The results from the Historical assemblages had suggested that seasonality and changes in climate were unlikely to have affected putrefactive bacterial bioerosion. The variation in bacterial bioerosion between similarly-aged remains from the same Later Prehistoric sites, as well as the subtleties of variation in bacterial attack by phase refuted the suggestion that climatic fluctuations were responsible for phase-specific differences in bacterial bioerosion.

7.1.2 Wedl Tunnelling

Wedl tunnelling was present within 18% of the study sample. In terrestrial environments, this type of alteration is associated with the exploitation of bone by extraneous fungi (Marchiafava *et al.* 1974; Jans *et al.* 2004; Fernández-Jalvo *et al.* 2010). This type of tunnelling usually occurred concurrently with bacterial attack within the current study sample. This result contrasted with the findings from previous studies which have found that fungal tunnelling usually occurs in isolation (Jans *et al.* 2004; Nielsen-Marsh *et al.* 2007). Wedl tunnelling was never observed to have destroyed significant proportions of the internal bone microstructure, and was mostly seen within small islands of well-preserved bone that had been missed by bacteria. The absence of Wedl bioerosion from bones that were free from non-Wedl MFD suggested that it was unlikely that prior fungal tunnelling had been erased by subsequent bacterial attack. A more likely scenario was that fungi invaded the bone after the body had skeletonised and targeted the areas of preserved bone microstructure that had been missed by putrefactive bacteria (Nielsen-Marsh & Hedges 2000; Jans *et al.* 2004).

The primary factor that influenced the presence of Wedl tunnelling was whether a bone had been retrieved from a cave. Bones from caves were significantly more likely to demonstrate Wedl tunnelling. The specific decompositional environment of the cave appeared to have encouraged fungal exploitation of bone collagen. Most of the bones from caves were never properly buried, and would have lain within a cold, moist, but aerated atmosphere up until the point at which they were retrieved. The link between Wedl tunnelling and cave deposition is supported by descriptions of cadaveric decomposition within cave environments, which recognise fungi as major contributors to later bodily decay in these contexts (Terrell-Nield & MacDonald 1997). This observation was consistent with the appearance of Wedl tunnelling within areas of bone that had been missed by putrefactive bacteria. Previous studies have suggested that fungal exploitation of bone is more likely to occur within bones that retain

some soft tissue, which was consistent with the taphonomic evidence from the cave assemblages that bones had been deposited as part of whole corpses (Marchiafava *et al.* 1974; Chamberlain 2001; Papakonstantinou 2009).

All samples of bones that did not originate from caves were likely to have been buried before or soon after decomposition. The lower rates of Wedl tunnelling within buried bones suggested that burial obstructs fungal exploitation of the bone microstructure. The types of fungus that are most capable of exploiting bone collagen may not be able access buried bone beyond a certain depth and may rely on open environments for the transportation of their spores. These results suggested that defleshed bones exposed to the air may be particularly susceptible to fungal exploitation.

There were significant differences in the occurrence of Wedl tunnelling between bones from different site assemblages after the cave bones were excluded. Most of the variation was controlled by Later Prehistoric site assemblages. Wedl attack appeared most often within samples of bones from four Later Prehistoric sites: Neat's Court, Brodsworth, Danebury and South Dumpton Down. The only Historical site assemblage that demonstrated higher occurrences of Wedl tunnelling was the Royal Mint. Analysis of the results from the Royal Mint identified that occurrences of Wedl tunnelling were higher within samples from skeletons found within the Abbey Church.

The significant site-specific differences in occurrences of Wedl tunnelling amongst bone samples suggested that deposition within a cave was not the only factor that encouraged fungal exploitation of bone. There was some suggestion that bodies recovered from underneath the Abbey Church at the Royal Mint site had been displayed before they were eventually interred (Grainger *et al.* 2008). Exposure of bone along with decomposing soft tissue in an open indoor environment may have been responsible for the slightly elevated occurrence of fungal Wedl tunnelling within these samples. The higher occurrence of Wedl tunnelling within bones from Later Prehistoric sites was notable given that Historical remains were likely to have been buried soon after death, whereas there was evidence that the Later Prehistoric bones had been subject to varied forms of treatment that may have involved sub-aerial exposure or entombment above ground (Cunliffe 1983; 1984; Barber *et al.* 1989; Perkins 1994; Annis *et al.* 1997; Chamberlain 1999; Parker Pearson *et al.* 2005; Darvill 2010; Lelong 2010; Vyner & Wall 2011; Lelong 2012). The association between Wedl tunnelling and Later Prehistoric sites combined with the evidence for the significant effect of cave deposition suggested that retention of a bone above ground or within an open aerated environment,

possibly whilst retaining some soft tissue, encouraged fungal exploitation of bone microstructure.

There was evidence from Danebury, Suddern Farm and Brodsworth that graves had been reopened before the bodies had skeletonised (Cunliffe 1983; Merrony 2012, personal communication). Bones from all of these sites demonstrated Wedl tunnelling. Similar *post mortem* processes had been implicated at other Later Prehistoric sites such as Hornish Point, South Dumpton Down and Cladh Hallan, but samples from these sites did not demonstrate fungal tunnelling (Barber *et al.* 1989; Perkins 1994; Parker Pearson *et al.* 2005). This observation suggested that retention of a bone above ground increased the chances, but did not guarantee it would be tunnelled by fungi. The precise conditions that encourage fungal exploitation of bone microstructure require further investigation.

The link between Wedl tunnelling and decomposition of a bone in an open environment may be consistent with previous observations that Wedl tunnelling is prevalent within the butchered archaeological bones of domesticated animals (Jans *et al.* 2004). Many of these butchered bones were likely to have been deposited as waste, possibly whilst retaining some soft tissue, in the open air, on the ground surface or within a rubbish tip (Jans *et al.* 2004). An association between Wedl tunnelling and decomposition of bone above ground suggested that the identification of Wedl bioerosion could be used to discern previous states of deposition that might otherwise leave no archaeological trace.

These findings suggest that unbioeroded bones deposited in open environments should provide prime targets for saprophytic fungi. However, the absence of Wedl tunnelling from unbioeroded samples of bone from Carsington Pasture Cave, where the majority of bioeroded samples demonstrated some Wedl tunnelling, detracted from this hypothesis. Perhaps prior bacterial bioerosion facilitates subsequent fungal attack to some extent. Jans *et al.* (2004: 91) noted that fungal attack usually appears in isolation within most archaeological bones. However, most archaeological bones sampled by Jans *et al.* (2004) had been buried and would not have experienced an open aerated environment that may have facilitated fungal bioerosion (Jans *et al.* 2004). The higher prevalence of fungal attack within the current human study sample may have occurred as a result of the inclusion of bones that experienced putrefaction followed by open conditions that enabled fungal exploitation. The successful experimental reproduction of fungal tunnelling within fresh bone samples combined with common occurrence of fungal tunnelling in isolation within butchered faunal material suggested that prior putrefactive bacterial bioerosion of bone is not prerequisite for fungal

exploitation (Marchiafava *et al.* 1974; Fernández-Jalvo *et al.* 2010). However, many of the archaeological butchered faunal bones sampled by Jans *et al.* (2004) may have been heated through cooking. The alteration of the bone mineral promoted by heating could have rendered the proteins more susceptible to exploitation by saprophytic fungi (Turner-Walker 2012).

7.1.3 Collagen Birefringence

The significant correlation between Whole OHI score and Birefringence Index confirmed that the primary mechanism of collagen loss amongst the primary study sample was microbial exploitation (Hackett 1981). All bones that demonstrated immaculate birefringence had been allocated OHI scores of five. This result was expected given that any histological destruction would have resulted in collagen loss and a reduction of birefringence (Hackett 1981). A small number of bone samples demonstrated immaculate levels of histological preservation but reduced or obliterated collagen birefringence. These bones were disparately spread amongst the whole study sample.

The loss of birefringence within histologically well-preserved thin sections could be attributed to one of two factors. Microstructural features were sometimes obscured within areas of thin sections that had been stained. Intense staining sometimes caused a corresponding loss of birefringence when the section was viewed under polarised light (Garland 1987; Grupe & Dreses-Werringloer 1993; Schultz 1997; Shahack-Gross *et al.* 1997; Hanson & Cain 2007; Turner-Walker 2008). Staining prevents light from refracting through the bone section, thereby dampening birefringence (Garland 1987; Grupe & Dreses-Werringloer 1993). Loss of birefringence that corresponded with areas of staining probably did not represent protein loss.

Loss of birefringence in certain histologically well-preserved samples could not be explained by microstructural staining. Birefringence reduction in these samples must have represented protein loss by a chemical rather than biological mechanism (Collins *et al.* 1995; Nielsen-Marsh *et al.* 2007; Smith *et al.* 2007). The survival of these bones into the archaeological record suggested that they had been subjected to accelerated chemical hydrolysis rather than acidic erosion (Gordon & Buikstra 1981; Collins *et al.* 1995; Smith *et al.* 2007). An acidic environment would normally promote destruction of the whole bone before it could enter the archaeological record (Gordon & Buikstra 1981; Smith *et al.* 2007).

Only seven bones used in the current study (2%) showed evidence for birefringence reduction through collagen hydrolysis. This figure was much lower than the 14% of archaeological bones from European Holocene sites that were found by Smith *et al.* (2007: 1491) to have been degraded by accelerated hydrolysis. The disparity between these figures may be attributable to the use of domesticate faunal material by Smith *et al.* (2007). Exposure of a bone to moderately high temperatures for extended lengths of time represents the only process that has been confirmed to promote accelerated collagen loss (Collins *et al.* 1995; Smith *et al.* 2002; Nielsen-Marsh *et al.* 2007; Smith *et al.* 2007; Abdel-Maksoud 2010). Some of the faunal material of the type that is obtained from archaeological sites is likely to have been subject to cooking processes that could have promoted chemical collagen loss (Collins *et al.* 1995; Abdel-Maksoud 2010; Koon *et al.* 2010).

The rarity of archaeological bones from temperate Europe that have been degraded through accelerated collagen hydrolysis suggested that specific environmental conditions or taphonomic events are likely to be responsible for this type of degradation (Nielsen-Marsh *et al.* 2007; Smith *et al.* 2007). Explanations for accelerated collagen loss include highly alkaline contexts or depositional environments that promote rapid wetting and drying cycles (Smith *et al.* 2002; Nielsen-Marsh *et al.* 2007; Smith *et al.* 2007). One of the ways in which a burial environment may be rendered sufficiently alkaline to promote collagen hydrolysis is through the application of lime (Smith *et al.* 2002). The only bone sample from the Royal Mint that demonstrated immaculate histological preservation but low collagen birefringence came from the skeleton that had been surrounded by lime (Grainger & Phillpotts 2011). This specimen provides some evidence that the increase in environmental alkalinity promoted by liming can promote accelerated collagen hydrolysis in bone.

Well-preserved samples of bone from Neat's Court and Danebury demonstrated reduced levels of collagen birefringence without any corresponding microscopic staining. There was macroscopic evidence that each of these specimens had been burnt (Cunliffe 1984; Morley 2010, personal communication). The evidence for accelerated collagen loss within these samples was consistent with the bones having been exposed to low levels of heat for extended durations. The implications of these results are discussed in the site-specific interpretation of diagenetic patterns.

The rest of the samples that demonstrated characteristics of accelerated collagen loss were distributed amongst the Bantycock and Carver Street assemblages. The conditions that promoted accelerated collagen loss within these samples were not apparent. The burial

environment of the Carver Street remains was wet and acidic (ARCUS 2004). Collagen loss amongst samples from this site may have been encouraged by periods of increased acidity rather than accelerated hydrolysis. Some of the bones from Carver Street were friable and demonstrated high numbers of microfissures to their internal microstructure. These features are consistent with acidic erosion, although microfissures can also appear within remains that have lost collagen through rapid hydrolysis (Gordon & Buikstra 1981; Smith *et al.* 2002; Turner-Walker & Jans 2008; Turner-Walker & Peacock 2008). There was no obvious reason for the loss of collagen birefringence amongst the Bantycock samples (Smith *et al.* 2002).

7.1.4 Persistence of the Periosteal Surface

The large proportion of samples that retained a preserved periosteal cortex (89%) contrasted with the proportion of bioeroded specimens. There was no relationship between the persistence of the periosteal surface and measures of bacterial bioerosion. These results agreed with the observations of previous studies that the survival of the periosteal cortex is unrelated to overall histological preservation and that this area is often immune to bacterial tunnelling (Hanson & Buikstra 1987; Jans *et al.* 2004; Turner-Walker 2008; Hollund *et al.* 2012). The common persistence of the periosteal bone surface is probably responsible for the lack of correlation between the macroscopic and microscopic measures of bone preservation (Hedges *et al.* 1995; Hedges 2002).

Previous studies have suggested that bacterial bioerosion of the periosteal surface is halted through the deactivation of collagenase and cross-linking of organic molecules by invasive humic acids from the burial soil (van Klinken & Hedges 1995; Hedges 2002; Jans *et al.* 2004; Turner-Walker 2008). This scenario does not make sense under an endogenous model of bioerosion, as enteric bacteria would be capable of accessing the bone long before it came into contact with the soil. The relationship between the persistence of the periosteal surface and microstructural staining was not investigated statistically. The observations that staining was most often observed at the periosteal and endosteal surfaces of bone samples were consistent with an association between the intensity of staining and periosteal preservation.

Humic factors have been linked with brown microstructural staining (Garland 1987; Grupe & Dreses-Werringloer 1993; Schultz 1997). Brown microstructural staining appeared within a small proportion of the samples used in the current study. It was unlikely that humic staining

was responsible for the survival of the periosteal surface amongst most bones included within the current study sample. Orange microstructural staining appeared much more often, but this type of discoloration has not been linked with humic substances or the persistence of the periosteal surface (Garland 1987; Grupe & Dreses-Werringloer 1993; Schultz 1997; Hollund *et al.* 2012). Brown staining was observed within both bioeroded and unbioeroded areas of bone thin sections. There was no evidence that the immunity of the periosteal surface to bacterial bioerosion was associated with microstructural staining.

A more likely explanation for the perseverance of the periosteal surface is the composition of the internal bone microstructure. Enteric osteolytic bacteria gain access to the bone through the vasculature within the Haversian canals (Bell *et al.* 1996; Jans *et al.* 2004). It is probable that bacteria travel down the canaliculi from the Haversian canal in order to begin attacking the bone microstructure from the osteocyte lacunae. This route allows bacteria to bypass the indigestible mineralised cement line that surrounds the Haversian canal (Bell *et al.* 1996; Hedges 2002; Jans *et al.* 2004; Turner-Walker 2008). Bone remodelling and secondary osteon formation is concentrated within the internal bone microstructure, leaving fringes of non-osteonal circumferential lamellar bone at the periosteal and endosteal peripheries (Junqueira *et al.* 1986; Kerley 1965). The osteocytes contained within circumferential lamellar bone are separated from osteolytic bacteria by at least one cement line. The perseverance of the periosteal surface within archaeological bone thin sections could be attributable to the lack of Haversian systems within circumferential lamellar bone, which denies direct access to invading bacteria.

Periosteal loss amongst the current study sample was caused by a destructive factor that was not linked to bioerosion. There was a statistically significant association between the presence of the periosteal surface and soil type. Samples of bones from silt environments were more likely to have lost their periosteal surface than those recovered from other types of soil. The correlations between the persistence of the periosteal surface and soil type suggested that this diagenetic parameter represented external mechanical erosion. Silt contexts more often encouraged periosteal loss, presumably through some process of weathering. There were no significant site-specific differences in levels of periosteal loss between bones that had been deposited within silt, although the difference was close to the significance threshold within the Holm-Bonferroni method (Appendix 2). Periosteal loss was most common amongst remains from Danebury Hillfort, Suddern Farm and Whitwell Quarry. Only two samples were obtained from Suddern Farm, and so it was difficult to establish the significance of this result. Silt burial environments did not result in equal proportions of periosteal loss. Site-specific variation in

periosteal loss amongst silt-deposited samples may have been attributable to the inadequacy of categories of soil type in capturing properties that affected bone degradation. On the other hand, site-specific differences in the composition of the silts may have controlled erosion of the periosteal bone cortex.

There was also a significant difference in the persistence of the periosteal surface between remains from different Later Prehistoric phases. Samples of Iron Age bones were more likely to have lost their periosteal surfaces. Most of the Iron Age bones had been recovered from silt burial contexts and so it was difficult to distinguish which variable was responsible for variation in this diagenetic parameter. Both silt burial environment and Iron Age date appeared to have had some independent influence on the survival of the periosteal cortex. The debateable status of phase as a measurement cultural change suggested that the best explanation for variation in periosteal cortex survival was that Iron Age bones had been subjected to a specific *post mortem* process that promoted cortical weathering. It was difficult to determine what other factors may have promoted phase-specific patterns in exogenous erosion. There was evidence that Iron Age remains from Danebury, Suddern Farm, South Dumpton Down and Bilham Farm had decomposed in open burial environments before being buried. Partial articulation of some of the skeletons from these sites suggested that bones had been handled and curated for a length of time before being deposited. The exposure of bone to the elements within these circumstances could have promoted cortical weathering and was likely to have been responsible for the increased prevalence of periosteal loss.

These results indicated that the loss of the periosteal surface may be useful in determining taphonomic histories of remains to a limited extent. Taphonomic processes that encouraged substantial weathering of the bone cortex are also to be reflected in rates of periosteal survival. These processes probably include burial within silt environments. Periosteal loss within samples of bone from non-silt contexts may be useful for inferring previous funerary treatment that would have produced significant cortical weathering, such as prolonged sub-aerial exposure.

7.2 VISUAL DIAGENETIC CHANGES

7.2.1 Orange Diagenetic Changes

Orange staining and orange inclusions represented the visual diagenetic features that were found most abundantly within the current study sample. There were statistically significant positive correlations between levels of orange staining, orange inclusions and infiltrations which indicated that the intensity of all of these features increased concurrently. However, some of the relationships between these features were not straightforward. Orange inclusions appeared more frequently within remains where orange staining was present. Frequencies of orange inclusions increased in remains that showed fair rather than superficial levels of orange staining. However, the frequencies of orange inclusions did not increase between remains that demonstrated fair and extensive orange staining.

The relationship between orange staining and the occurrence of infiltrations was fairly linear. Bones that were free from orange inclusions demonstrated much lower occurrences of infiltrations. However, the occurrence of infiltrations did not vary with the frequencies of inclusions. The occurrence of infiltrations was related to the presence or absence of inclusions rather than their intensity. The association between infiltrations and inclusions supported qualitative observations that infiltrations commonly surrounded osteons that had been densely packed with orange inclusions. These results suggested that infiltrations represented areas where orange inclusions had spilled out of the natural porosities into the surrounding microstructure. Measures of orange inclusions related to their frequency rather than their intensity within natural porosities, and so an increase in the measure of inclusions used in the current study did not correlate with an increase in occurrences of infiltrations.

Both orange staining and infiltrations varied significantly with burial soil. The relationship between orange inclusions and soil type was close to significant within the Holm-Bonferroni method (Appendix 2). These results were consistent with the suggestion that visual diagenetic changes are promoted by features of the burial environment (Garland 1987; Shahack-Gross *et al.* 1997). The relationship between sediment and visual diagenetic change was emphasised by the results from the samples of bones from Carsington Pasture Cave. These bones were not recovered from sediment and were the only samples allocated to the ‘Open’ soil type category. Orange visual diagenetic changes were absent or low within samples of bone from this site.

The significant associations and similar colours of these visual diagenetic changes suggested that they represented different consequences of interactions between the bone and a particular mineral present within most burial environments (Garland 1987; Grupe & Dreses-Werringloer 1993; Schultz 1997; Shahack-Gross *et al.* 1997; Hanson & Cain 2007). Correlations between these features and burial soil suggested that this mineral had originated from the burial context, rather than having formed *in situ* (Hollund *et al.* 2012). This conclusion was supported by the evidence that orange diagenetic changes sometimes varied with spatial distribution of skeletons across sites, although this kind of patterning was not present within all parameters at all locations.

Previous studies of bone diagenesis have associated orange-coloured diagenetic features with ferrous materials, particularly iron oxides (Garland 1987; Grupe & Dreses-Werringloer 1993; Schultz 1997; Shahack-Gross *et al.* 1997; Hanson & Cain 2007). The ubiquity of archaeological bone interaction with iron oxides would be unsurprising given that it is one of the most soluble minerals commonly found within soils and is often responsible for their pigment (Schwertmann 1991; 1993). The best explanation for the correlation between orange visual diagenetic parameters and their variance with soil type was that they all represented expressions of iron oxides that had entered the bone through different mechanisms.

The concentration of orange staining at the periosteal and endosteal surfaces of thin sections was consistent with the suggestion that this parameter represented diffusion of iron oxides into areas of bone that were in direct contact with the burial matrix. Inclusions were likely to represent iron oxides that had been transported into the natural porosities by percolating groundwater (Garland 1987: Schultz 1997). Infiltrations most likely represented extreme forms of either of these outcomes that had enabled large accumulations of iron oxides to penetrate the bone matrix. The different distributions of these features within certain bones must have been related to how far properties of particular environments altered the ways in which iron oxides interacted with the bone microstructure (Garland 1987; Schultz 1997; Shahack-Gross *et al.* 1997).

The overarching factor that would have affected these features would have been the abundance of iron oxides within the immediate burial environment. Spatial distributions of orange diagenetic features within remains from particular sites indicated that localised availability of iron oxides affected the abundance of orange changes. Abundance of iron oxides within the environment is likely to have had the largest effect on bone staining, as staining appeared most frequently within areas of bone that were in contact with the burial sediment.

However, the dependence of inclusions and infiltrations on percolating groundwater would indicate that these features would have been secondarily influenced by soil moisture content and mobility. The discussion below provides some attempt to explain the disparate patterns of variation in orange visual diagenetic parameters with soil type in terms of differences in properties of the burial environments.

7.2.1.1 Orange Staining

Orange staining was almost non-existent amongst remains from silt and open contexts, mostly absent within bones from sands, while superficial in bones from clays, and more extensive amongst bones from gravels. These results suggested that iron oxides were not abundant within the sand and silt contexts. The exact chemical composition of each of the burial soils was unknown, but their probable constitution was consistent with a lack of iron oxides. Sands are mostly constituted of silica and quartzes which are unlikely to encourage significant orange pigmentation. The silt burial contexts consisted of either limestone or chalk rubble, two rock types that are also unlikely to promote significant discolouration of bone in of themselves (Cunliffe 1983; Perkins 1994; Cunliffe & Poole 2000; Vyner & Wall 2011).

There were significant site-specific differences in orange staining between bones that had been interred within clays. No site assemblage could be identified as singularly explaining this variation. Microstructural staining was rarely consistent within assemblages of bones from single sites, which indicated that variation in properties of soils across sites was likely to have affected the intensity of orange staining. The intensity of orange microstructural staining varied with spatial distribution of remains within the Royal Mint cemetery, which was a gravel site. Orange staining was most commonly found within remains from the eastern cemetery, which had yielded bones that had been contaminated by chemicals that had entered the soil as a result of industrial activities associated with the Royal Mint (Grainger *et al.* 2008). Higher levels of staining within samples of bones from these areas may have been related to the presence of these chemicals (Grainger *et al.* 2008). Spatial patterning of orange-stained bones was not apparent within most site assemblages, although spatial distribution could only be recorded crudely in most cases. It was likely that unknown unrecorded site-specific factors had influenced levels of orange staining in certain instances

There was a close-to-significant association between orange staining and charnel assemblages. This association persisted within site assemblages that included samples of both charnel and non-charnel remains. Whether a sample originated from a charnel bone also affected the occurrence of orange inclusions and infiltration. Samples of charnel material were more likely to be free from or demonstrate lower levels of orange staining. It was difficult to justify how charnelling practices may have affected orange staining within a model where this diagenetic parameter was primarily affected by the nature of the surrounding burial environment. The charnel bones were subject to the same post-excavation processes as articulated remains. Any relationship between charnelling and orange staining must have been produced by some aspect of charnelling that reduced interactions between the bone and the burial environment. One possible explanation was that charnelled bones were not placed back in sediment soon after they were exposed, but were kept above ground for a length of time before being reinterred. The disinterred bones may have been left on the ground surface or stored within a purpose-built structure such as an ossuary before being reburied. The time spent above ground would have ensured that charnel bones would not have interacted with the burial environment to the same extent as articulated deposits.

The problem with this explanation was that all of the charnel bones that had been sampled had eventually been reinterred and had laid within soil for a number of centuries before being excavated. Any period of disinterment would be relatively insignificant compared to the time the bone spent in the ground and therefore it is difficult to envision charnelling having had a significant impact on overall interactions with the burial environment. It would be expected that bones would have to be retained above ground for a significant length of time in order to affect comparative levels of microstructural staining. If charnelling was responsible for levels of orange staining then this diagenetic parameter may have some use in reconstructing taphonomic processes linked to treatment of remains, rather than just the nature of the burial sediment. Anomalously low levels of orange staining within a sample of bone from an assemblage could be used to suggest that the specimen had been retained above ground for a certain length of time. However the potential influential effects of local burial conditions would compromise any such inferences.

7.2.1.2 Orange Inclusions

The factor that was found to have had the largest significant influence on frequencies of orange inclusions was whether a sample came from a charnel bone. The strength of this influence was uncertain, as when this factor was placed by itself within a regression model, it no longer enacted a significant influence on orange inclusions. However, similar interactions between other orange visual diagenetic changes and charnel remains suggested that there was a relationship between orange inclusions and charnelling.

Samples from charnel bones demonstrated lower levels of orange inclusions. This relationship persisted within samples of bones from Black Gate but not Bolsover, where the extent of orange inclusions was the same amongst samples from charnel and non-charnel bones. Reduced periods of time spent interacting with the burial environment was the only conceivable explanation for differences in levels of orange inclusions between charnel or non-charnel remains. Such an explanation would suggest that orange inclusions form gradually within bone samples over a number of centuries. Only a slow process could have been responsible for charnel bones demonstrating a deficiency of visual diagenetic features compared to consistently buried bones after they had been reinterred for a number of centuries. It is possible that levels of orange inclusions could be used to infer certain aspects of anthropogenic taphonomic treatment rather than just environmental factors.

Soil type did not have a significant effect on orange inclusions when the Holm-Bonferroni method was employed (Appendix 2). However, the results from regression analysis approached significance and the measure of orange inclusions was highly correlated with infiltrations and orange staining, which both shared significant relationships with burial soil. Bones from silt and open contexts demonstrated lower levels of orange inclusions than those from all other environments. Bones from silt and open contexts explained the majority of the soil-specific variation in orange inclusions. Frequencies of orange inclusions were similar within samples of bones from all other soil types when the charnel bones were excluded. The low levels of orange staining found within remains from silt contexts was attributed to the low levels of iron oxides within the burial environment, and the same factor was probably responsible for the dearth of orange inclusions within the same category of remains (Garland 1987; Schultz 1997). The higher frequencies of orange inclusions found within the remains from sand contexts contrasted with the lack of orange staining. Frequencies of Inclusions are likely to be linked to the availability of iron oxides but also the mobility of groundwater. The

discrepancy between levels of orange staining and inclusions suggested that iron oxides were not common within the sands that directly surrounded sampled skeletons. Ferrous minerals must have found their way into bone porosities from elsewhere through groundwater action.

There was a significant difference in the frequency of orange inclusions amongst bones from silt sites. The majority of variation was explained by the Danebury and Suddern Farm site assemblages. Levels of orange inclusions within bone samples from these sites were particularly low. Levels of orange inclusions within samples of silt-deposited bones from remaining site assemblages were similar to those amongst site assemblages from non-silt contexts. The Danebury and Suddern Farm site assemblages had been interred within chalk burial environments, which would have contained relatively low levels of iron oxides. The other silt-deposited bones had been interred amongst limestone silt. Levels of orange staining did not vary significantly between different site assemblages from silts. The result from the orange inclusions suggested that although iron oxides had not often been in direct contact with bones from silts and had not differentially affected levels of staining, they occurred often enough within non-chalk silts to be transported into the bone microporosities via percolating groundwater. This result highlighted that although measures of orange visual diagenetic changes reflected the results of similar processes, there were differences in their variations based on the specific circumstances that promoted their occurrence.

7.2.1.3 Infiltrations

The presence of infiltrations was significantly influenced by soil type. Bones from sands, silts and open environments demonstrated similarly low levels of infiltrations, whereas these features were observed abundantly within bones from clay and gravels. There were significant differences in the occurrences of infiltrations within different site assemblages that had been interred within clay. These results indicated that the frequency of infiltrations was related to the burial environment and was controlled by the nature of the burial soils as well as site-specific conditions (Garland 1987; Grupe & Dreses-Werringloer 1993; Schultz 1997; Shahack-Gross *et al.* 1997).

The patterns of infiltrations amongst samples of bone from different soil types were very similar to the variability in levels of staining. The similarity in the distributions of these two diagenetic forms suggested that occurrence of infiltrations was related to the abundance of

ferrous mineral within the burial environment (Garland 1987; Grupe & Dreses-Werringloer 1993; Schultz 1997; Shahack-Gross *et al.* 1997; Hollund *et al.* 2012). The high correlation between orange staining and infiltrations ran contrary to the observations that infiltrations represented the consequence of compact inclusions. However, this observation was likely to be the result of the inclusion recording method, which focussed on the number of natural porosities affected rather than the amount of material present. Most of the variation amongst the orange infiltrations was explained by the presence or absence of inclusions, whilst inclusion frequency appeared to be inconsequential. The suggestion that infiltrations formed in environments that included high levels of iron oxides indicated that an abundance of this mineral was likely to encourage the deposition of excess materials within natural porosities, enabling the formation of infiltrations.

The lack of difference in occurrences of infiltrations amongst different site assemblages from silt and sand burial soils suggested that site-specific variability had little effect on infiltrations when iron content of the soil was low. However, there was some suggestion of spatial variation in infiltrations amongst samples of bone from Bantycock, and the Royal Mint. Spatial distribution of infiltrations amongst the samples of bone from the Royal Mint followed the same pattern as orange staining and was similarly likely to be the result of ground contamination by chemicals associated with the minting process.

Whether a bone originated from a charnel deposit was also found to have influenced infiltrations. Infiltrations occurred less commonly within charnel bones. This influence approached significance under the Holm-Bonferroni method (Appendix 2). The relationships between charnelling and other orange visual diagenetic changes suggested that this result was pertinent. Infiltrations were consistently found in lower frequencies within samples of charnel bone from site assemblages that included both charnel and non-charnel remains. Like orange staining and inclusions, the only explanation that could be provided for this relationship was that retention of the bone above ground reduced the time a bone spent interacting with iron oxides in the burial environment and limited the occurrence of infiltrations relative to bones that had not been disinterred. This result suggested that it might be possible for measures of infiltrations to be used in inferring anthropogenic treatment of remains in cases where influential effects of the burial environment could be controlled.

7.2.1.4 Orange Visual Diagenetic Changes and Anoxia

Hollund *et al.* (2012) found that iron oxides had accumulated within archaeological bones as a result of bodily decomposition within an anoxic environment. It was important to establish whether iron oxides were a signifier of previous anoxic conditions within the current study sample, as such environments would have interrupted putrefaction and may have been responsible for significant variation on measures of bacterial bone bioerosion (Bottrell *et al.* 1998; Turner-Walker 1999; Turner-Walker & Jans 2008; Hollund *et al.* 2012). There was evidence that most of the current study sample had interacted with materials that caused orange microstructural alteration. None of the measures of orange diagenetic change had been significantly influenced by anoxic conditions.

It was possible that subtle differences between orange visual diagenetic features could have provided a way of discerning between structures that had formed as a result of anoxic decomposition or interactions with ferrous materials in the environment (Turner-Walker & Jans 2008; Hollund *et al.* 2012). However, all orange inclusions were amorphous and often demonstrated the full range of variation in shapes and hues within single bone samples. Categories of orange inclusions could not be satisfactorily divided using thin section light microscopy. The correlation between measures of orange aesthetic diagenetic changes indicated that they all represented manifestations of the same process.

Framboidal pyrite formations are usually present within bones from bodies that decomposed under anoxic conditions (Bottrell *et al.* 1998; Turner-Walker 1999; Turner-Walker & Jans 2008; Hollund *et al.* 2012). This compound would only have formed in the presence hydrogen sulphides produced by decomposing organic matter (Hollund *et al.* 2012). The techniques of microscopy used in the current study could not be used to identify framboidal pyrites effectively because of the level of variation within the ubiquitous orange inclusions. The limited means of the current study suggested that orange visual diagenetic changes were present within most archaeological samples and were related to the levels of iron oxide within the immediate burial environment. Whilst orange diagenetic changes to bone are likely to form as a result of anaerobic bodily decomposition, these changes occurred too commonly within archaeological bones used in the current study for them to be used to say anything of use about the conditions of early decomposition.

The likelihood that orange microstructural changes were indicative of burial environments that interfered with bodily decomposition was investigated additionally through tests of

associations between visual diagenetic features and Whole OHI score (Turner-Walker & Jans 2008; Hollund *et al.* 2012). Moreover, other researchers have linked the appearance of visual diagenetic features with the composition of the burial sediment (Garland 1987; Grupe & Dreses-Werringloer 1993; Shahack-Gross *et al.* 1997; Hanson & Cain 2007). Categories of burial sediment had been crudely defined, and so variation in visual diagenetic features provided an extra method of assessing the relationship between burial sediment and bacterial bone bioerosion. Any significant relationships between these features would have jeopardised the results of the analysis of bacterial bone bioerosion discussed above. However there were no significant associations between orange microstructural changes and Whole OHI in the current study. These results combined with the divergent explanatory variables that were found to have influenced bacterial bioerosion and visual diagenetic change suggested that these two types of microstructural alteration were not related to one another.

Variations in the three types of orange diagenetic alterations were compared against measures of bacterial bioerosion within samples of bone from anoxic sites. These specific tests were performed to establish whether the relationship between visual diagenetic changes and bacterial bioerosion was different between bones from anoxic and aerobic environments. Bones that demonstrated higher levels of histological preservation would have originated from bodies that decomposed under anoxic conditions from an early stage and would be expected to demonstrate increased levels of orange microstructural change. One of the samples from Carver Street had been extensively stained orange, although beyond this single observation there were no further relationships between orange staining, orange inclusions and histological preservation. Infiltrations appeared more commonly within samples of bones from Carver Street that were histologically well-preserved. None of the measures of orange diagenetic features correlated with Whole OHI score amongst the Coronation Street site assemblage. These results indicated that decomposition within anoxic environments amongst the current study sample had not affected levels of orange microstructural change. If iron oxides were produced within these kinds of environments then they had a negligible effect on the levels of visual diagenetic features that had been promoted by interactions between the bones and the burial environments (Garland 1987; Grupe & Dreses-Werringloer 1993; Schultz 1997; Shahack-Gross *et al.* 1997). This result supported the finding that infiltrations of bone by iron oxides were not necessarily indicative of environmental conditions that interfered with bacterial bone bioerosion.

The association between orange diagenetic features and burial soil meant that lack of correlation between measures of bacterial bioerosion and orange microstructural alterations

provided further evidence that bacterial bioerosion did not correspond with composition of the burial matrix and could not account for the variation in bacterial attack within the Later Prehistoric assemblage. These conclusions must be accompanied by the caveat that the thin section light microscopy method was not the best technique for identifying differences between visual diagenetic changes. However, within the confines of the current study these results suggested that the explanations for variations in bacterial bioerosion amongst the whole study sample discussed above remained valid.

7.2.2 Other Visual Diagenetic Alterations

Comparisons of the different types of visual diagenetic changes established that the remaining categories, brown staining, yellow staining and grey inclusions, were not related to one other, nor to measures of orange microstructural change. Theses specific visual diagenetic changes occurred within small proportions of the study sample. The relationship between these isolated phenomena and other recorded variables will be discussed in order to determine if these features were indicative of factors that had influenced bacterial bone bioerosion as well as whether they could be of any use in inferring aspects of early taphonomic processes. The rare occurrence of these visual diagenetic features amongst this study sample meant that any conclusions regarding their influence and variation would have to be taken with caution.

7.2.2.1 Brown Staining

Bones that demonstrated brown microstructural staining comprised only 13% of the total number of stained bones. Variation in brown staining was not influenced by any of the variables that were recorded for the current study. There was no significant variation in brown staining between bones from different sites. Brown-stained bones were absent or appeared only sporadically within bone from most sites, and only occurred frequently within samples from Frälsegården, Ingleby Barwick and Cnip Headland. The single specimen from Langwell Cist demonstrated the highest levels of brown staining. Factors specific to these sites must have encouraged brown staining within these bones. The results from orange diagenetic changes and previous studies of other sample sets had suggested that visual diagenetic changes were

likely to have been caused by interactions with substances in the burial environment (Garland 1987; Grupe & Dreses-Werringloer 1993; Shahack-Gross *et al.* 1997; Jans *et al.* 2004).

There was evidence that bones from Ingleby Barwick, Cnip Headland and Langwell Cist decomposed within enclosed environments that had contained large quantities of organic material (Annis *et al.* 1997; Lelong 2011; 2012). Brown staining has commonly been attributed to infiltration of the bone by humic acids from burial soils (Garland 1987; Grupe & Dreses-Werringloer 1993; Shahack-Gross *et al.* 1997; Reiche et al. 2003; Jans *et al.* 2004). Humic acids are formed through the decomposition of organic matter. The Langwell Cist specimen was covered in a large cow hide, and the stained Ingleby Barwick bones had been contained within a wooden cist (Annis *et al.* 2007; Lelong 2012). Most of the sand that directly surrounded the remains recovered from Cnip had been discoloured brown, presumably as a result of decayed organic matter (Lelong 2011). It was likely that the brown microstructural bone staining at these three sites had been caused by humic factors released by decaying organic grave goods. However, it was probable that a significant proportion of the whole study sample had lain within environments that contained appreciable quantities of decaying organic matter, such as coffins, but most did not demonstrate brown microstructural staining. The paucity of brown staining amongst Historical bones suggested that quantities of decaying organic matter within the burial environment did not always induce brown microstructural staining. The extent of brown staining was most likely influenced by the proximity of the organic matter to the bone combined with features of the burial environment that facilitated the diffusion of brown-staining elements, such as moisture content and mobility.

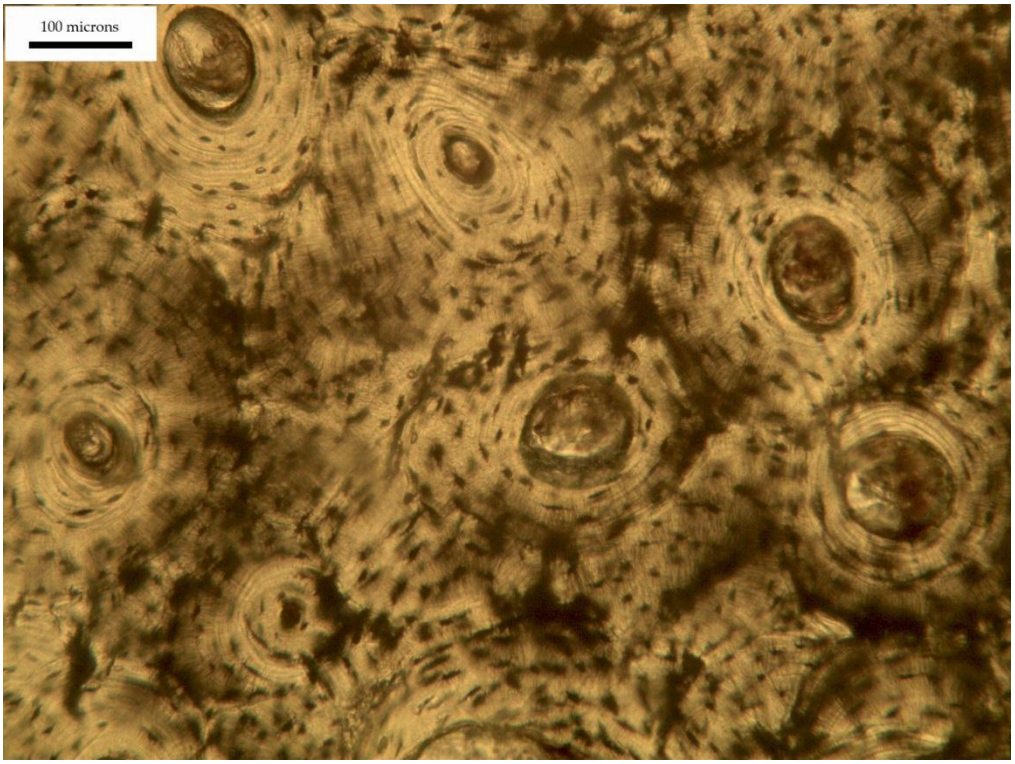

Image 7.1: Micrograph of a transverse femoral thin section from the Langwell Cist individual. Bioerosion is absent from areas of the microstructure that have been variably stained brown (taken by the author).

There was no significant association between brown staining and Whole OHI score within the Holm-Bonferroni method (Appendix 2). This result refuted the notion that humic acids prevent bacterial bone bioerosion (Hedges 2002; Jans *et al.* 2004; Turner-Walker 2008). Both stained and unstained areas of single thin sections could remain unbioeroded (Image 7.1). These observations could be explained by one of three scenarios: brown staining was not always a result of humic infiltration, humic acids did not significantly inhibit bacterial exploitation of bone proteins or the bone was stained after it had been bioeroded by bacteria. The results from the current study sample suggested that that brown staining could sometimes be used to identify remains that had been previously surrounded by decaying organic matter. However, the low proportion of samples that demonstrated this type of staining combined with the inconsistencies between brown staining and the presence of organic material suggested that this type of microstructural change would not provide a reliable indicator of taphonomic circumstances. Further investigation of brown staining in archaeological bones is required to define its cause and confirm any possible uses in taphonomic reconstructions.

7.2.2.2 Yellow Staining

Yellow staining was present within 5% of the bones sampled for this study, which represented only 8% of the total number of stained samples. In some specimens it was unclear whether the yellow staining represented a discrete form of alteration or a weaker version of the orange discolouration. There was no statistically significant difference in yellow staining between bones taken from different sites. Yellow staining was equally infrequent amongst all site assemblages. The extent of yellow staining was only more than superficial in two samples of bone from the Royal Mint site and one from Danebury. The two Royal Mint samples demonstrated fair levels of yellow staining. Several skeletons excavated from the Royal Mint had been contaminated and discoloured macroscopically by waste chemicals produced during the minting process (Grainger *et al.* 2008). The two yellow-stained samples originated from the eastern part of the Royal Mint site that demonstrated most evidence for chemical contamination. It was likely that yellow staining within the Royal Mint samples had been caused by contamination from chemicals within the burial environment. The Royal Mint was built centuries after interment at the site had ceased, and so it was unlikely that this contamination had interfered with bodily decomposition and bone bioerosion (Grainger *et al.* 2008).

The single sample recovered from the Danebury hillfort that demonstrated extensive yellow staining had been taken from a bone that showed macroscopic discolouration indicative of burning (Cunliffe 1984). This specimen demonstrated a non-biotic reduction in collagen birefringence that was consistent with heat treatment (Collins *et al.* 1995; Smith *et al.* 2007; Abdel-Maksoud 2010). Burning bone at low temperatures produces a yellow or tan colour within the microstructure. Low-level burning represented the best explanation for the discolouration of the Danebury sample (Shahack-Gross *et al.* 1997; Hanson & Cain 2007; Squires *et al.* 2011). The yellow-stained bone specimens from these two sites suggested that this type of discolouration was associated with specific taphonomic events.

The presence and intensity of yellow staining was positively correlated with Whole OHI score. The result of this correlation approached significance within the Holm-Bonferroni method (Appendix 2). However the crux of this positive correlation was the single extensively-stained sample that had been allocated a Whole OHI score of five. There was no linear distribution of yellow staining scores amongst variably-bioeroded samples that had not been allocated a Whole OHI score of five. The anomalous sample comprised the burnt bone from Danebury, the

discolouration of which was not the result of infiltration by a substance that had prevented bacterial bioerosion. The small number of remains that demonstrated yellow staining meant that the Danebury sample had an undue influence on tests of correlation. The discussions had established that yellow staining was likely to have occurred as a result of disparate site-specific processes. The correlation between yellow staining and bacterial bone bioerosion was unlikely to have occurred as a result of a single process that interrupted putrefaction, and was probably a remnant of small sample size. The exact processes that are responsible for yellow microstructural staining would need to be discerned before this factor could be of any use to reconstructions of taphonomic processes.

7.2.2.3 Grey Inclusions

Frequency of grey inclusions within the study sample was significantly influenced by soil type, which added to the evidence that visual diagenetic changes were influenced by interactions with the burial environment. Grey inclusions were found almost exclusively within samples of bone recovered from silts and open environments. Further tests of the distributions of grey inclusions amongst site assemblages that had been deposited in silt produced a significant result. Grey inclusions were only identified within samples of bone from Danebury and Suddern Farm. This finding was the inverse of the results from the orange inclusions and suggested that all inclusions formed as a result of similar processes involving different materials from the burial environment. The bones from Suddern Farm and Danebury had been surrounded by chalk silt and domestic waste (Cunliffe 1983; 1984; Cunliffe & Poole 2000). It was probable that grey inclusions found in bone samples from these sites represented deposits of calcite that had been transported into the bone from the burial environment by percolating groundwater (Garland 1987).

Grey inclusions were also found amongst the remains recovered from Carsington Pasture Cave. However, the nature of these inclusions was quite different to those found within the bones from silt contexts. Inclusions from silt-deposited bone were rounded, whilst those observed within the Carsington Pasture Cave remains consisted of large crystalline structures. Some of the bones from Carsington Pasture cave were noted to have been covered by limestone speleothem, and it was likely that these inclusions represented the internal precipitation of this material (Chamberlain 1999; Papakonstantinou 2009).

Frequencies of grey inclusions did not correlate with bacterial bone bioerosion. This result provided further proof of the separateness of the processes that produce these types of diagenetic changes within archaeological bone. These results supported the overall findings that visual diagenetic changes relate to long-term interactions between a bone and substances within the immediate burial environment and were mostly unrelated to other types of bone diagenesis.

7.3 MUMMIFIED REMAINS

Samples of bone from mummified bodies were included in the current study in order to establish whether remains that had been afforded such treatment demonstrated characteristic patterns of bone bioerosion. Preservation of soft tissues usually requires some circumvention of putrefaction and theoretically mummified bone would be expected to demonstrate limited or no bacterial tunnelling depending on the efficacy of the preservative method. The few bones of mummies that have been studied previously have all been free from microbial bioerosion (Weinstein *et al.* 1981; Thompson & Cowen 1984; Hess *et al.* 1998). However, all of these mummified samples had been preserved in ways that would have had an immediate effect on putrefaction. Both of the mummified remains sampled for the current project had been preserved through natural processes, which may not have efficiently circumvented putrefaction (Kelly 2012). These samples should be useful in establishing variation in levels putrefactive bioerosion within mummified bone.

7.3.1 Derrycashel Bog Body

The intense and consistent red staining observed within the Derrycashel thin sections was unlike the types of discolouration found within the archaeological bones recovered from conventional burial environments in both its colour and distribution. Staining within the archaeological bones used in the current study was usually orange, yellow or brown, and concentrated at the periosteal and endosteal surfaces. It was reasonable to conclude that the staining of the Derrycashel sample was specific to the deposition of bone within a bog environment. Similar red-brown colouring is often observed in bog water run-off (Painter

1995). This pigment occurs as a result of dissolved tannic acids produced by the decaying organic material within the bog (Painter 1995). The discolouration of the Derrycashel bone was most likely a result of infiltration by similar substances. Painter (1995; 1998) suggested that soft tissue preservation in bog bodies is caused by the presence of tannins such as sphagnan, which is released by decaying *Sphagnum* moss (Painter 1995). Sphagnan produces Maillard reactions within bodily proteins, which cross-link the intrinsic polypeptide chains, rendering them invulnerable to most processes of decomposition (Painter 1995; 1998). The intense staining and high levels of organic preservation observed within the Derrycashel bone samples were both symptomatic of tannic acid infiltration (Jahnel & Frimmel 1994; Painter 1995; 1998).

The dark inclusions recorded within the Derrycashel bone were opaque, non-crystalline, irregular and were likely to be organic (Garland 1995; Schultz 1997). The morphology and pigment of these inclusions were very different from those observed within the archaeological remains used in the Primary Analysis. Garland (1995: 107) described similar organic inclusions within the bone microstructure of the mummified cranium recovered from Worsley Moss and concluded that they were microscopic fragments of *Sphagnum* moss. It is likely that the organic inclusions represent the same material in both cases, although the morphology of the inclusions from the Derrycashel remains resembled remnants of blue-green algae desmids, rather than microscopic *Sphagnum* (Woerlkerling 1976).

In common with other bones samples extracted from mummified remains, the histological preservation of the bone microstructures in the Derrycashel specimens was excellent (Weinstein *et al.* 1981; Thompson & Cowen 1984; Hess *et al.* 1998). Collagen birefringence within the Derrycashel specimens was also high, which indicated that the bone protein structures had been preserved (Hackett 1981). The focal points of collagen loss observed within the Derrycashel specimens superficially resembled natural enlarged osteocyte lacunae. However whilst the sizes of osteocyte lacunae can fluctuate within and between fresh bone samples, they have not been noted to grow and coalesce as they had within the Derrycashel specimens (Maximow & Bloom 1957; Junqueira *et al.* 1986). These enlarged osteocyte lacunae were particularly conspicuous because of the deficiency in typical osteocyte lacunae within the Derrycashel bone samples. Many osteons were free from microstructures that resembled osteocyte lacunae. The appearance of enlarged osteocyte lacunae was independent of the presence of normal-sized lacunae.

Osteocyte lacunae were also notable by their absence from the microstructure of the mummified human head excavated from Worsley Moss (Garland 1995: 107). The loss of

osteocyte lacunae within the bones of the Derrycashel individual must have occurred as a result of exposure to the bog environment. Osteocyte lacunae are commonly observed to have disappeared from the microstructure of cremated human bones (Forbes 1941; Hanson & Cain 2007). Hanson & Cain (2007) reasoned that the obliteration of osteocyte lacunae in cremated bone was as a consequence of the evaporation of moisture content and fusion of the hydroxyapatite mineral crystals which resulted in a loss of bone mass. Osteocyte lacunae are thought to disappear because they represent convenient cavities into which the bone structure can collapse to compensate for this loss of mass (Hanson & Cain 2007). Bones deposited in bogs lose mass through demineralisation encouraged by chemicals within the environment (Painter 1995). This loss of bone mass most likely caused the collapse of the osteocyte lacunae in the Derrycashel and Worsley Moss samples (Hanson & Cain 2007). This reasoning highlights the likely diagenetic origin of the enlarged osteocyte lacunae. The survival of these features in areas where conventional osteocyte lacunae had been lost indicated that the enlarged types represented cavities within the bone microstructure, rather than variations in the natural porosities that bone lamellae naturally circumvent and subsequently collapse into during bone shrinkage.

Enlarged coalescent osteocyte lacunae have been associated with progressive demineralisation and biological attack of bone microstructure (Gordon & Buikstra 1981; Bell *et al.* 1996). Turner-Walker & Peacock (2008: 158) noted that the gradual demineralisation of Scandinavian bog-deposited cow metapodials involved the enlargement and amalgamation of osteocyte lacunae and associated canaliculi. Gordon & Buikstra (1981) and Turner-Walker & Jans (2008) found similar diffuse patterns of enlarged osteocyte lacunae in archaeological human bones that had been deposited in acidic soils. The acidity of the bog environment has often been used as an explanation for bone demineralisation (Turner 1995). However Painter (1995) and Turner-Walker & Peacock (2008) demonstrated that bone demineralisation in bogs more often occurs as a result of the action of *Sphagnum* moss. The live *Sphagnum* holocellulose sequesters calcium as well as other multivalent cations, as does the sphagnan acid that is produced when the moss dies and transforms into peat (Painter 1995: 90). In most other corrosive acidic burial environments, both phases of the bone substrate are rapidly destroyed (Gordon & Buikstra 1987; Nielsen-Marsh *et al.* 2007; Smith *et al.* 2007; Turner-Walker & Jans 2008). If bog acidity was to blame for bone demineralisation, it would be difficult to account for the selective destruction of mineral and conservation of protein that was apparent in the Derrycashel bones (Turner-Walker & Peacock 2008; Kelly 2012). The processes by which *Sphagnum* and its by-products can both remove the mineral and preserve

the protein have been articulated in detail (Painter 1995). Therefore, it was plausible that *Sphagnum* rather than the acidity was primarily responsible for the demineralisation of the Derrycashel bone.

The focal destruction present within the Derrycashel thin sections did not adhere precisely to the morphology of Hackett's (1981) bacterial MFD. Chemical bone demineralisation forms a diffuse 'wave' of destruction, beginning at the periosteal edge and moving inwards (Gordon & Buikstra 1981; Turner-Walker & Jans 2008; Turner-Walker & Peacock 2008; Fernández-Jalvo *et al.* 2010). The points of collagen loss in the Derrycashel samples were more abundant towards the periosteal aspects, but were generally distributed sporadically throughout the thin sections. The points of collagen loss did not conform to a progressive wave of destruction model (Turner-Walker & Peacock 2008). The Worsley Man skull was retrieved from a similar demineralising environment, yet demonstrated no enlarged osteocyte lacunae (Garland 1995). The enlarged lacunae identified within the Derrycashel sample were not associable with a demineralising environment, and must have occurred as a result of bacterial collagen loss.

Hackett's (1981: 250) specific MFD forms represent an advanced level of osteolytic decay, and it is likely that there are various stages to their formation (White 2009). It is known that non-Wedl MFD are formed from smaller amalgamations of cavities, the microbial spongiform porosity (Jackes *et al.* 2001; Turner-Walker *et al.* 2002). White (2009) found that non-Wedl MFD begin as smaller dark cavities that resemble enlarged osteocyte lacunae. Non-Wedl MFD in archaeological bone are usually concentrated around osteocyte lacunae that appear enlarged (Hackett 1981; Hanson & Buikstra 1987; Bell 1990; Bell *et al.* 1996; Jans *et al.* 2004). The distribution of focal collagen loss within the Derrycashel samples was similar to that observed within partially biodegraded archaeological specimens, which demonstrate dispersed accumulations of non-Wedl MFD that intensify towards the sub-periosteal zones (Hackett 1981; Hanson & Buikstra 1987; Child 1995a; Jans *et al.* 2004; Jans 2008; Hollund *et al.* 2012).

The lack of characteristic hypermineralised zones from the borders of the areas collagen loss located within the Derrycashel remains prevented an unequivocal confirmation of the presence of Hackett's (1981: 250) non-Wedl MFD (Jans *et al.* 2004; Jans 2008). However, the lack of hypermineralised zones might be expected, considering that the Derrycashel remains had been extensively demineralised. Non-bacterial micro-organisms such as mosses and algae are capable of exploiting bone protein in certain circumstances. Exogenous blue-green algae (cyanobacteria) have been identified as the likely culprits involved in the bioerosion of bones recovered from aquatic contexts (Bell & Jones 1990; Bell *et al.* 1996). The presence of biomass

within the Derrycashel specimens that resembled cyanobacteria could provide an explanation for the observed bioerosion. However, cyanobacterial bioerosion is characterised by Wedl MFD, which were absent from the Derrycashel thin sections (Hackett 1981; Bell & Jones 1990; Bell & Elkerton 2008; Turner-Walker & Jans 2008). If the cyanobacteria were responsible for the collagen loss, there should have been an association between the presence of inclusions and the areas of degradation. However, there was no relationship between the organic inclusions and the microscopic tunnelling, even in areas of the thin sections where the algae appeared to have infiltrated the bone microstructure. There was no evidence of biological destruction in the bone microstructure of the head recovered from Worsley Moss, despite this specimen containing organic inclusions similar to those observed in the Derrycashel samples (Garland 1995). The lack of enteric bioerosion in the Worsley Head was predictable as trauma in its associated vertebrae indicated that the head was separated from the major source of endogenous bacteria (*i.e.* the rest of the body) in the early *post mortem* period (Garland 1995; Nielsen-Marsh *et al.* 2007).

The identification of bacterial bioerosion within the incompletely-mummified Derrycashel thin sections supported the hypothesis that the bones of mummies will be bioeroded by putrefactive bacteria if the method of preservation is inconsistent and fails to suspend putrefaction soon after death (Jans 2008; White 2009). The Derrycashel specimens represented the first bones obtained from a mummified body that demonstrated lesions that were likely to have occurred as a result of biotic collagen loss. The pattern of decomposition within the Derrycashel samples suggested that the bones had been subjected to the initial stages of bacterial attack before putrefaction was halted by the preservative environment (Jans *et al.* 2004; Nielsen-Marsh *et al.* 2007; Jans 2008; Hollund *et al.* 2012). This finding supported the proposal that bodies placed within peat bogs will be subject to variable levels of decomposition before putrefaction is eventually curtailed. This conclusion was consistent with the sporadic preservation of soft tissue observed within bog bodies generally and in the Derrycashel body specifically.

The lack of visible circumferential lamellar bone within the Derrycashel bone samples suggested that most of the periosteal third had been lost. Thus, the part of the Derrycashel bone that was most likely to have been extensively attacked by bacteria was not present (Jans *et al.* 2004; Parker Pearson *et al.* 2005; Hollund *et al.* 2012). It was possible that the loss of the periosteal surface of the Derrycashel samples has led to an underestimation of microscopic decay. The loss of the periosteal surface itself may have occurred as a result of intense bacterial bioerosion within the sub-periosteal zone. Initial putrefactive bioerosion may have

removed a quantity of collagen from the sub-periosteal bone before the sphagnan infiltration began to take effect (Painter 1995; 1998). When the elements in the bog began to decalcify the bone, the previous microbial-induced collagen loss would have ensured the complete collapse of the periosteal surface up until the point where the bacterial attack had been halted (Painter 1995; Turner-Walker & Peacock 2008). This theory could explain why the bones of some bog bodies have entirely disintegrated whilst the soft tissue has remained intact (Turner 1995). White's (2009) histological study of buried pig carcasses found that bone which retained large quantities of soft tissue often demonstrated extensive levels of bacterial collagen loss. The inhibitory effects of sphagnan are not consistent within as well as between bog body specimens, and it is likely that putrefactive bone bioerosion is equally as variable (Painter 1995; Turner 1995). Therefore the presence or absence of bones within bog bodies may be dependent on the extent to which the endogenous putrefactive microbiota were able to exploit the bone before they were neutralised by the encroaching bog chemicals.

7.3.2 Yemeni Desiccated Mummy

In addition to the mummified Yemeni patella, two further patellae had been analysed to provide a characterisation of the microstructure and morphology of diagenesis within this specific little-analysed bone. The provenances of both of these samples was unknown, but based upon their condition and context it was likely that one was an archaeological bone that originated from a British Historical cemetery and the other was a modern fresh sample. The high levels of bacterial bioerosion observed within the British archaeological patella confirmed that this skeletal element is susceptible to extensive putrefactive bacterial attack. The histological preservation of the patella from the Yemeni mummy was comparable to the fresh bone sample. Collagen birefringence within the Yemeni patella was high, although it was slightly reduced towards the periosteal surfaces, which indicated that collagen had been lost from the outer fringes of the bone via a non-biological mechanism. The high microstructural preservation of the Yemeni patella was consistent with previous histomorphological characterisations of bone from mummified individuals.

There were notable occurrences of enlarged osteocyte lacunae within the Yemeni patella. These phenomena would normally be regarded as representing variation in natural phenomena, however the results of White (2009) combined with observations of similar features within the bone of the Derrycashel individual suggested that these features

represented the beginnings of bacterial bioerosion. These features were concentrated within the sub-periosteal zone of the patella. This patterning emulated the distribution of non-Wedl MFD with archaeological bones and the samples from the Derrycashel individual. Examination of the thin section of the Yemeni patella under polarised light demonstrated that the enlarged osteocyte lacunae obliterated natural collagen birefringence, which indicated that they represented collagen loss (Hackett 1981). It was possible that these features represented the beginnings of putrefactive osteolytic bioerosion, although it was difficult to say for certain, as the focal destruction was not as advanced as that which was observed within the Derrycashel individual as well as White's (2009) pig bones.

The Yemeni mummy had been preserved naturally within a hot desiccating burial context (Brothwell 2010, personal communication). The enteric visceral bacteria would have been rapidly deprived of the moisture they required for their proliferation as soon as the body entered the burial matrix. It was not surprising that levels of putrefactive bioerosion within this sample were lower than what was observed within the partially-mummified Derrycashel sample. The presence of focal points of collagen loss within the Yemeni individual suggested that putrefaction was initiated to some extent before the corpse had dried out. Therefore the bone from the Yemeni sample further confirmed that high levels of histological preservation are sustained within bone from mummified remains, but also hinted that these bones are not immune from internal bacterial bioerosion.

Accumulations of small microfissures were identified at the periosteal edges of the Yemeni patella thin section, particularly around sites that were attached to soft tissue. The size and shape of these microfissures suggested that they had not occurred as a result of sample preparation trauma, which are usually regularised in line with the path of the cutting blade, but had a diagenetic aetiology (Schultz 1997). The microfissuring corresponded with areas of birefringence loss at periosteal zones. It was likely that the bone had cracked because of the loss of mass that had resulted from the chemical removal of protein (Smith *et al.* 2002; 2007). Microfissuring and loss of collagen is consistent with bone diagenesis by accelerated hydrolysis (Smith *et al.* 2002; Nielsen-Marsh *et al.* 2007; 2007). Collagen hydrolysis within the Yemeni sample was likely to have been accelerated by the high temperatures of the burial environment (Collins *et al.* 1995; Smith *et al.* 2002; 2007).

The microstructure of the Yemeni patella had not been stained and did not include any infiltrations. However, this specimen included frequent inclusions. These inclusions consisted of accumulations of regular rounded brown particles. These features did not resemble the

types of inclusions found commonly within the archaeological bone used in the Primary Analysis, which were much more irregular in size and colour. It was probable that the inclusions within the Yemeni patella consisted of small particles of sand that had infiltrated the bone through the natural porosities.

7.3.3 Summary of the Results from the Mummified Material

The results from the histological analysis of both mummified sample found that microstructural preservation was high. This result was consistent with previous histomorphological studies of bone from mummified bodies and provided further evidence for the link between putrefaction and bacterial bone bioerosion (Weinstein *et al.* 1981; Thompson & Cowen 1984; Hess *et al.* 1998). These results contrasted with the histological preservation of the Historical archaeological remains and indicated that mummified bodies are the only category of ancient articulated remains that consistently demonstrate high levels of histological preservation. Articulated post-neonatal remains that had not decomposed under anoxic conditions rarely demonstrated high levels of histological preservation, and in this sense, this diagenetic signature was characteristic of mummified bone.

However, the Derrycashel specimen and the Yemeni sample to a lesser extent indicated that mummified bone is not immune from bacterial bioerosion. Inefficient methods of mummification can expose the bones to minimal levels of putrefactive bioerosion. Therefore, the diagenetic signature of mummification bone is a scale ranging from minimal to no levels of bacterial bioerosion. This result confirmed that the pattern of bioerosion observed within the remains of the adult male recovered from Bronze Age Cladh Hallan was consistent with prior mummification (Parker Pearson *et al.* 2005). The characterisation of the effects of mummification on bone histology and the rarity of this histological signature within most archaeological bone suggested that analysis of archaeological bone microstructure would provide a useful tool for identifying skeletons that had been previously mummified, but had subsequently lost their soft tissue (Parker Pearson *et al.* 2005). Occurrence of inclusions and staining within both samples was consistent with the notion that these features represent interactions between the bone and elements within the burial environment (Garland 1987).

8 SPECIFIC DISCUSSION

The results discussed in the previous chapter established that patterns of bacterial bioerosion within post-neonatal remains recovered from aerobic burial environments reflected how far the early *post mortem* treatment of an individual had facilitated bone exposure to putrefaction bacteria (Jans *et al.* 2004; Nielsen-Marsh *et al.* 2007; Smith *et al.* 2007). The exact treatment that was afforded the Later Prehistoric individuals that were included in this study was uncertain. Distributions of Whole OHI scores across remains each Later Prehistoric site assemblage had been compared against the Historical baseline in order to establish how bacterial bioerosion varied from what would be expected to have occurred as a result of immediate burial.

This next chapter mostly consists of reports that combined the taphonomic information from each Later Prehistoric site and forensic studies of bodily decomposition with the results from the histological analysis of the human bone to formulate interpretations of mortuary rites that had been practised in each case. Some of these reports had already been produced for institutions that were responsible for the curation of each respective assemblage as part of agreements that had facilitated sampling. These discussions provide exemplary studies that demonstrate the potential utility of bone histology in inferring funerary rite when combined with other contextual information.

The results from the whole assemblage had suggested that there were phase-specific trends in patterns of bacterial bone bioerosion amongst the Later Prehistoric remains that likely translated into the practise of particular mortuary rites. Therefore, discussion of the results from each Later Prehistoric site were grouped by Later Prehistoric Phase. Each grouping of reports was followed by a discussion of results from all bone samples that belonged to the same phase. This discussion only covered those treatments that best explained the patterns of bone diagenesis and taphonomy within the bones used in the current study. It was not the intention of this review to infer the types of rites that were practised all over Britain during these time periods, although widespread performance of a particular kind of treatment might be inferred circumstantially if the same kinds of processes were identified at contemporaneous sites from different parts of the country. However all of these interpretations must be accompanied by the caveat that there was probably much regional and temporal variation in funerary activities within specific Later Prehistoric periods (Darvill 2010).

8.1 DEVIANT TREATMENT OF INFANTS

There is evidence from several past and modern societies that the bodies of neonates or young infants are often subject to a deviant form of funerary treatment (Murphy 2008). There were some notable patterns in the distribution of histologically well-preserved neonatal bones from some of the site assemblages that merited further discussion regarding the recognition of their possible deviant treatment. All of the neonatal remains from the Roman Bantycock settlement that did not demonstrate any bacterial bioerosion originated from isolated discrete graves located within the settlement itself, rather than the associated cemetery (Pre-Construct Archaeology 2005). It was possible that these potentially stillborn babies had been afforded a deviant form of funerary treatment. However, adult remains were also recovered from the settlement contexts, albeit less frequently. The cemetery dated to the later phase of activity at the site, and it was possible that a designated burial ground did not exist during earlier periods (Pre-Construct Archaeology 2005). The only neonatal sample that was sampled from the cemetery came from the foetus that was found *in situ* within the skeleton of its mother (Pre-Construct Archaeology 2005).

Differential deposition of stillborn remains may also have been practised at Bolsover. High numbers of neonatal remains was recovered from the north side of the Saint Mary & Saint Laurence church (Foster 1992). A large proportion these neonatal skeletons were free from bacterial bioerosion (Foster 1992). Documentary evidence had suggested that in this area of the country during the period the cemetery was used, the north side of the church was reserved for burials of deviant individuals, such as cases of suicide or unbaptised infants (Foster 1992; Kerr 1994). Therefore the abundance of possible stillborn individuals from the north side of the church may be significant. However, only one neonatal skeleton was sampled from outside of the north side of the church. This sample had been extensively bioeroded and was therefore likely to have originated from an infant that had lived for a short while after birth.

The cluster of partially-articulated neonatal remains recovered from Carsington Pasture Cave had been radiocarbon dated to the Late Bronze Age/Early Iron Age (Chamberlain 1999). The specific ages-at-death, Iron Age date, partial state of articulation and localised nature of these remains suggested that they comprised a separate depositional event to the rest of the human bones, which were representative of all age-at-death categories, had been extensively disarticulated around the cave chamber and had produced a Late Neolithic/Early Bronze Age radiocarbon date (Chamberlain 1999; Papakonstantinou 2009). Both skeletons that were

sampled from the neonatal cluster were free from bioerosion. The partial articulation and completeness of the neonatal skeletons suggested that the cave represented their primary depositional context and that their partial disarticulation had occurred as a result of later disturbance (Chamberlain 1999; Papakonstantinou 2009).

These observations suggested that Carsington Pasture Cave was used for the exclusive deposition of stillborn neonatal remains in the Iron Age. Iron Age remains are not often recovered from cave sites (Cunliffe 1991). Most human remains that date to this period have been recovered from within discrete monuments, cemeteries or settlements (Cunliffe 1991). The exclusivity of the Iron Age neonatal deposits meant that it was tempting to interpret this assemblage as having resulted from the deviant deposition of stillborn infants. However, the few radiocarbon dates that were obtained from the site ensured that this interpretation was tenuous.

8.2 LATER PREHISTORIC INTERPRETATIONS

8.2.1 Mesolithic/Neolithic

8.2.1.1 Havnø Shell Midden, Denmark

Bacterial bioerosion within the remains from the Havnø were unlikely to have been influenced by environmental inconsistencies, preservational biases or the effects of diverse skeletal part representation. Bacterial bioerosion of the bone from Havnø could be taken to represent the extent to which a skeletal element had been exposed to putrefaction bacteria, and so the histological results could be used to make some cautious inferences regarding funerary practices (Bell *et al.* 1996; Jans *et al.* 2004; Nielsen-Marsh *et al.* 2007; Hollund *et al.* 2012). It could not be known whether each bone represented a specific individual, and it was likely that certain samples originated from a single skeleton (Andersen 2008).

All of the bones from Havnø demonstrated some level of bacterial bioerosion, but there was a dichotomy between those that had been extensively and sparingly bioeroded. This patterning suggested that at least two separate funerary rites were represented at Havnø. Both of these processes led to the disarticulation of the skeleton before the bones were interred in the midden. The bias of the OHI scoring method towards middle grades became relevant to the

study of the Havnø bones when specimens UBQ-a and LOU-a were considered. Both bones were given OHI scores of two, but whilst UBQ-a retained almost fifty-per-cent of its histological integrity, the LOU-a specimen retained only around twenty-per-cent. The histological destruction observed within UBQ-a was closest to that recorded within the better-preserved group and this specimen most likely represented an outlier to this distribution. Therefore, the two groups of Havnø bones that represented the putative discrete funerary practices consisted of the poorly-preserved specimens: NSV, THE and LOU-a, and the well-preserved specimens: UBQ-a, QQB, XPG, NYA, VNV, UBQ-b, PCE-a and OHL-3.

The well-preserved Havnø bone specimens must have been derived from individuals that were subjected to a *post mortem* process which limited bone exposure to putrefactive bacteria (Bell *et al.* 1996; Jans *et al.* 2004; Parker Pearson *et al.* 2005; Nielsen-Marsh *et al.* 2007; Hollund *et al.* 2012). Sub-aerial exposure could account for this pattern of bacterial bioerosion (Rodriguez & Bass 1983; 1985; Simmons *et al.* 2010). Variation in bacterial bioerosion was possibly related to the time of year each individual decomposed (Galloway *et al.* 1989; Bass 1997; Archer 2004; Carter *et al.* 2007; Michaud & Moreau 2011; Zhou & Bayard 2011). However, a study of bacterial bioerosion in bones taken from sub-aerially exposed mammalian remains found no correlation between bacterial attack and season of death (Fernández-Jalvo *et al.* 2010). It is probable that a complex combination of environmental variables affect bodily decomposition and bacterial bioerosion of bone within sub-aerially exposed cadavers (Fernández-Jalvo *et al.* 2010). The inconsistency in representation of skeletal elements amongst the Havnø assemblage meant that the possibility that different skeletal elements were variably prone to bacterial bioerosion could not be dismissed entirely (Hanson & Buikstra 1987; Jans *et al.* 2004).

The poorly-preserved Havnø specimens had been subjected to high levels of putrefactive attack consistent with immediate inhumation of an intact body (Rodriguez & Bass 1983; 1985; Bell *et al.* 1996; Bass 1997; Rodriguez 1997; Jans *et al.* 2004; Nielsen-Marsh & Hedges 2000; Nielsen-Marsh *et al.* 2007; Hollund *et al.* 2012). The disarticulation of the Havnø remains suggested that whole bodies must have been primarily buried elsewhere. However, the poorly-preserved Havnø bones all originated from lower limbs or extremities, and it was possible that the replicated fibula fragments, NSV and UBQ-a, originated from the same individual (Hellewell 2012, personal communication). Histological preservation across the poorly-preserved Havnø bones was variable, but the fibula fragments were similar in terms of the severity of their bioerosion. It was feasible that all of the poorly preserved Havnø bones originated from a single individual that was buried intact within the midden and subsequently disturbed by later activity.

The Havnø bone thin sections all demonstrated types of orange staining, inclusions and infiltrations that were commonly found within the majority of archaeological samples used in the current study. The inclusions observed within the Havnø thin sections were consistent with deposits of iron oxides that precipitate out of percolating groundwater within the natural bone porosities (Garland 1987; Grupe & Dreses-Werringloer 1993; Schultz 1997; Hollund *et al.* 2012). The orange staining that appeared at the periosteal and endosteal fringes in certain of the Havnø thin sections was probably caused by diffusion of iron oxides that occurred as a result of these external surfaces lying in contact with the burial medium (Grupe & Dreses-Werringloer 1993; Hollund *et al.* 2012). Inconsistent brown staining of the type observed within the Havnø samples has most often associated with infiltration by humic acids released by decaying organic matter (Garland 1987; Grupe & Dreses-Werringloer 1993; van Klinken & Hedges 1995; Shahack-Gross *et al.* 1997). There was a slight association between the presence of brown staining and evidence for previous organic grave goods within the study sample used in the Primary Analysis. The Havnø midden would have contained an abundance of decomposing organic matter that could have been responsible for the brown staining (Andersen 2008). The uniformity of these phenomena across the Havnø samples added to the evidence that these bones had been subjected to similar burial conditions over the period of their deposition.

The histological analysis of specimens from the Havnø assemblage revealed that the remains represented two possible funerary treatments that resulted in skeletal disarticulation. The histological signatures of most of the bones suggested that the individuals had been excarnated by sub-aerial exposure before their bones were interred in the midden. The histological signatures of the rest of the bones were consistent with primary burial. All of the bones that demonstrated low levels of histological preservation may have belonged to the lower limbs of a single individual. Therefore, it was possible that all of the extensively bioeroded samples from Havnø originated from a single individual that had been buried in articulation within the midden and was subsequently disarticulated by later disturbance.

8.2.2 Neolithic

8.2.2.1 Beeston Tor Cave CX, Staffordshire, U.K.

All four samples recovered From the Beeston Tor CX cave demonstrated high levels of bacterial attack to their internal microstructures. The Beeston Tor assemblage was disarticulated and comingled. This assemblage included a single neonatal femur. The poor level of histological preservation of this sample suggested that this individual was not likely to have been stillborn. This individual had been subjected to the same diagenetic processes as the rest of the bone sampled from Beeston Tor CX.

One sample, the femur of a two to three-year-old child, demonstrated slightly higher levels of histological preservation. Over fifty-per-cent of the internal microstructure of this sample remained intact. However, the overall results suggested that all bones had been subjected to high levels of putrefactive decay, similar to what would be expected to have occurred within remains that had been buried intact soon after death (Rodriguez & Bass 1983; 1985; Bell *et al.* 1996; Bass 1997; Rodriguez 1997; Jans *et al.* 2004; Nielsen-Marsh & Hedges 2000; Nielsen-Marsh *et al.* 2007). The most immediate interpretation of diagenesis within this assemblage was that the bodies were originally defleshed through primary burial and the disarticulated bones were deposited in the Beeston Tor CX cave.

It was assumed that the sample taken from Beeston Tor CX was representative of the assemblage as a whole. However, there was evidence that treatment of the remains deposited within the Beeston Tor CX cave may have varied. Radiocarbon dates of bones from the same comingled assemblage produced disparate dates within the Neolithic (Chamberlain 1999). A tibia of a child that was not sampled for thin sections analysis demonstrated cut marks indicative of dismemberment (Papakonstantinou 2009). These observations suggested that the Beeston Tor CX assemblage had accumulated over a significant length of time as a result of variable processes (Chamberlain 1999; Papakonstantinou 2009).

The interpretation of primary burial at Beeston Tor CX appeared to contradict the taphonomic evidence from the site, which had suggested that whole bodies had decomposed within the cave (Chamberlain 1999; Papakonstantinou 2009). Forensic studies of cadaveric decomposition within structures and caves have established that bones would have experienced variably high levels of putrefactive bioerosion mediated by the extent to which the environment facilitated access to skeletonising insects (Galloway *et al.* 1989; Goff 1991; Terrell-Nield & MacDonald 1997). Patterns of bacterial attack observed within the bones from

cave environments used in the current study were variably high and consistent with the model of indoor decomposition proposed by forensic experiments (Galloway *et al.* 1989; Goff 1991; Terrell-Nield & MacDonald 1997). The higher histological preservation of the bone from the child hinted at potential variability in bacterial bioerosion that was consistent with the signatures of cave samples taken as a whole. Only five-per-cent of samples within the Historical baseline distribution demonstrated Whole OHI scores of three. It was possible that low sample size at Beeston Tor CX had captured a skewed distribution of variation in bacterial bioerosion, or that this specific cave environment was more effective in preventing entomological access to cadavers (Goff 1991; Terrell-Nield & MacDonald 1997).

All of the bones from the Beeston Tor assemblage demonstrated Wedl bioerosion. Wedl tunnelling was found commonly within remains from caves. It has been suggested that the presence of soft tissue on the bones would facilitate fungal exploitation, which provides further support for the suggestion that the remains had been deposited within the cave in the early *post mortem* period (Marchiafava *et al.* 1974; Terrell-Nield & MacDonald 1997). Fungal decomposition characterises the late stages of cadaveric decay within caves (Terrell-Nield & MacDonald 1997). It was probable that the specific, dark, cold, damp but aerated conditions of the cave encouraged fungal tunnelling in the Beeston Tor CX samples.

The analysis of the entire assemblage had identified that staining, inclusions and infiltrations were directly related to the burial environment. Such features observed within the Beeston Tor assemblage must have occurred as a result of coverage by speleothem or after bones had been incorporated into the cave sediments. All staining inclusions and infiltrations were of an orange colour, consistent with those found within the majority of the bones sampled for this study, and probably indicative of infiltration by iron oxides (Garland 1987; Grupe & Dreses-Werringloer 1993; Schultz 1997; Hollund *et al.* 2012).

The histological and taphonomic evidence from the Beeston Tor CX cave suggested that at intact human remains were left to decompose on the cave surface at several points during the Neolithic. The skeletons were disarticulated and comingled through a combination of faunal and human disturbance before being incorporated within the sediments inside and at the entrance of the cave. Whilst the skeletons lay on the ground surface their bones were degraded further by saprophytic fungi.

8.2.2.2 Carsington Pasture Cave, Derbyshire, U.K.

The Carsington Pasture Cave assemblage consisted of partially-articulated and entirely disarticulated remains (Chamberlain 1999; Papakonstantinou 1999). All of the bones were recovered from the surface of the cave and showed no markings of having previously been interred within sediment (Chamberlain 1999; Papakonstantinou 1999). Samples of bone from the cave had been variably attacked by bacteria. Most bone samples that were free from bacterial attack originated from the cluster of partially-articulated Iron Age neonatal remains recovered from the second chamber. The possible treatment of the Iron Age neonatal remains was discussed above.

Two post-neonatal bone samples from Carsington Pasture Cave were free from microbial bioerosion, which indicated that they had not been exposed to putrefaction. One of the samples originated from a mostly-complete partially articulated skeleton. The other sample came from a disarticulated jumble of bones that may have all belonged to a single individual. The second of these skeletons demonstrated cut marks indicative of dismemberment (Chamberlain 1999; Papakonstantinou 1999). If dismemberment had occurred soon after death, the bones would have been removed from the soft tissues and organs before visceral bacteria were able to access the internal microstructure (Bell *et al.* 1996; Jans *et al.* 2004; Nielsen-Marsh *et al.* 2007). This process represented best explanation for the lack of bacterial bioerosion within the second individual.

No cut marks were detected on the partially articulated remains that were also free from microbial bioerosion. Initial partial disarticulation through sub-aerial exposure could have been responsible for the low levels of putrefactive bioerosion within these remains. However, this process only variably inhibits putrefactive bacterial bioerosion of the bone (Rodriguez & Bass 1983; 1985; Bell *et al.* 1996; Fernández-Jalvo *et al.* 2010; Hollund *et al.* 2012). The similar high levels of histological preservation observed within the cut-marked skeleton circumstantially suggested that both sets of remains had been dismembered. This process would not necessarily have left tell-tale cut marks on the bones (Guilday *et al.* 1962; Binford 1981; Fisher 1995). The similarity in skeletal part representation between the histologically well-preserved remains added circumstantial support to the suggestion that they had been treated analogously. The completeness of the dismembered skeletons and the close proximity of their bones suggested that these processes had taken place within or around the cave and that this environment represented the primary depositional context (Chamberlain 1999; Papakonstantinou 2009).

The rest of the post-neonatal remains from Carsington Pasture Cave demonstrated variably poor levels of histological preservation, which indicated that they had been exposed to extensive soft tissue putrefaction. Whole OHI scores of the bioeroded remains accumulated around scores of two and were elevated compared to the Historical baseline distribution. These results suggested that whilst most of the bioeroded remains from Carsington Pasture Cave had experienced intense levels of putrefaction, these processes had progressed variably, and in some cases may not have run their full course. This pattern was likely to be representative of bone from a body that had decomposed within the cave environment (Terrell-Nield & MacDonald 1997). Primary interment of whole bodies within Carsington Pasture cave was supported by the taphonomic analysis of distribution and representation of the human skeletons at the site (Chamberlain 1999; Papakonstantinou 2009).

The majority of the post-neonatal remains from Carsington Pasture Cave had not been dated, and those that had provided wide possible ranges. The most elegant scenario was that all of the non-neonatal samples had been deposited during the Neolithic or Early Bronze Age. It was possible that the two dismembered skeletons represented separate phases of activity. However, evidence for disparate rites is not necessarily indicative of different phases of activity within British Later Prehistoric periods, where there is evidence for the contemporaneous practise of discrete rites (Darvill 2010). Dismemberment may have represented a deviant form of funerary treatment.

Wedl tunnelling was identified within small sections of all but one of the bioeroded human bone samples from Carsington Pasture Cave. Fungal incursion was associated with cave interment amongst the entire sample set and probably occurred as a result of the bone having lain within an open, aerated environment that facilitated fungal exploitation, possibly whilst retaining some soft tissue (Terrell-Nield & MacDonald 1997; Jans *et al.* 2004). The suggestion that soft tissue facilitates fungal exploitation of bone collagen supported the notion that fleshed bodies had decomposed within the cave (Marchiafava *et al.* 1974; Terrell-Nield & MacDonald 1997).

The association between visual diagenetic changes and burial environment was consistent with the low levels of staining, inclusions and infiltrations observed within the Carsington Pasture cave specimens, which had never been placed within burial sediment (Garland 1987; Grupe & Dreses-Werringloer 1993; Schultz 1997; Hollund *et al.* 2012). Bones that had been covered in flowstone demonstrated specific crystalline inclusions that were most likely representative of speleothem incursion. Some inclusions resembled the orange variety that

were common to many of the archaeological bone sampled in this study. These features were likely to consist of iron oxide deposits produced by occasional water movement through the cave (Garland 1987; Grupe & Dreses-Werringloer 1993; Schultz 1997; Hollund *et al.* 2012).

8.2.2.3 Frälsegården Chambered Tomb, Falbygden, Sweden

All of the samples taken from the Frälsegården specimens demonstrated high levels of bacterial bioerosion, which indicated that they had been treated in ways which exposed the remains to extensive soft tissue putrefaction. However, the differences between the Whole OHI scores of the Frälsegården articulated and disarticulated human assemblage suggested that the articulated samples had been exposed to significantly lower levels of putrefactive attack. These signatures of bone bioerosion and skeletal articulation indicated that there were two separate funerary traditions represented within the Frälsegården assemblage; an earlier rite that had encouraged skeletal disarticulation and exposed the bones to high levels of putrefactive bioerosion and a later practice that promoted skeletal articulation whilst variably reducing levels of bacterial bioerosion (Sjögren 2011, personal communication).

Bacterial alteration of the disarticulated samples was characteristic of immediate burial (Rodriguez & Bass 1983; 1985; Bell *et al.* 1996; Nielsen-Marsh & Hedges 2000; Jans *et al.* 2004). These remains may have been defleshed by primary burial before they were exhumed and placed within the tomb. However, it was probable that the tomb promoted environmental conditions similar to those that would be found within a cave or indoor environment. The lower temperatures and diminished levels of insect activity within the Frälsegården chambered tomb would have promoted slow, unabated bodily decomposition (Galloway *et al.* 1989; Goff 1991; Terrell-Nield & MacDonald 1997). The simplest interpretation of the pattern of bone diagenesis amongst the Frälsegården disarticulated assemblages was that the remains had been interred directly within the tomb and were disarticulated by subsequent deposition and disturbance.

The lower levels of histological preservation observed amongst the disarticulated Frälsegården bones compared to remains from Carsington Pasture Cave and Beeston Tor suggested that initial primary burial still represented a plausible explanation. However, the original sampling of the Frälsegården remains had included a specimen from an articulated dog that had been interred directly within the chambered tomb. The articulation of this specimen suggested that the pattern of decomposition represented what would be expected from immediate interment

within the tomb (Sjögren 2011, personal communication). The pattern of bacterial bioerosion within the dog skeleton was analogous to that observed within the samples of disarticulated human bone. Whilst this result had to be tempered with the caveats regarding the appropriateness of comparing bacterial bioerosion within bone from different species, it supported nonetheless the suggestion that bacterial attack within the disarticulated human remains was a result of primary interment within the tomb. Frälsegården lies on a higher latitude than Carsington Pasture Cave and Beeston Tor. Higher levels of bacterial bioerosion within the Frälsegården remains may have been attributable to the colder climate, which would have reduced skeletonising insect activity (Rodriguez & Bass 1983; 1985; Terrell-Nield & MacDonald 1997; Campobasso *et al.* 2001; Vass 2011).

Levels of bacterial bioerosion within the articulated and partially articulated Frälsegården remains were variable but less extensive than those observed within the disarticulated specimens. The results the Carsington Pasture Cave and Beeston Tor CX had suggested that deposition within a cave or indoor environment promotes variable levels of bacterial bone bioerosion, and it was possible that signatures of bioerosion within all of the Frälsegården samples could be explained by direct decomposition cadavers within the tomb (Terrell-Nield & MacDonald 1997). However, the equal divisibility of the samples by bioerosion, articulation and chronology could not be ignored. These results suggested that the higher levels of skeletal articulation amongst the later deposits was not a result of gradual disarticulation from disturbance over time, but was attributable to a change in the way the dead were treated (Sjögren 2011, personal communication).

The patterns of bacterial bioerosion observed within the samples from articulated and partially articulated bones suggested that they had been subjected to processes that had an inconsistent effect on putrefaction (Bell *et al.* 1996; Jans *et al.* 2004; Nielsen-Marsh *et al.* 2007). There was no evidence that the sediments within the chamber were ever anoxic or would have promoted an environment that would have inhibited putrefaction (Sjögren 2011, personal communication). If whole cadavers had been interred directly within the tomb, it was likely that they were left decay on the ground surface within the open chamber, and not surrounded by sediment (Sjögren 2010). It was possible that bacterial bioerosion within the articulated and partially-articulated remains had been curtailed by the remains having been deposited initially within an inhibitory context (Parker Pearson *et al.* 2005; Hollund *et al.* 2012). However, patterns of bacterial bioerosion within these remains were more extensive than those observed within the anoxic-deposited Historical samples.

The link between level of articulation and Whole OHI score in the Frälsegården human assemblage suggested that an anthropogenic process linked to maintenance of bodily form were responsible for higher levels of histological integrity (Sjögren 2011, personal communication). The increased levels of skeletal articulation refuted the possibility that these samples had been sub-aerially exposed, as this treatment would have encouraged rapid skeletonisation and disarticulation (Rodriguez & Bass 1983; 1985; Simmons *et al.* 2010). One possible explanation was that these remains had been heavily wrapped. Wrapping of some of the Frälsegården remains was suggested by their level of articulation and highly flexed postures (Sjögren 2010). Wrapping has been found to interfere with bodily decomposition in certa*in situ*ations, although the results of the current study suggested that wrapping or clothing had little overall effect on putrefactive bone bioerosion (Mant 1987; Galloway *et al.* 1989; Mann *et al.* 1990; Goff 1992; Aturaliya & Lukasewycz 1999; Campobasso *et al.* 2001; Fielder & Graw 2003; Kelly *et al.* 2009; Vass 2011; Voss *et al.* 2011; Fereira & Cunha 2013).

Most studies of wrapping have suggested that this factor only inhibits putrefaction when augmenting other environmental influences such as aridity or water saturation (Mant 1987; Galloway *et al.* 1989; Fielder & Graw 2003; Vass 2011). The patterns of putrefactive bioerosion observed within the articulated and partially-articulated Frälsegården samples could be explained had they been initially wrapped and placed within a wet anoxic context that facilitated adipocere formation before they were interred within the tomb. Such a process may account for the partial articulation of some of the Frälsegården remains, particularly where they constituted the legs and pelvis, as adipocere commonly forms in areas that are high in body fat such as the thighs and buttocks (Mant 1987; Mann *et al.* 1990; Janaway 1996; Forbes *et al.* 2005). However, levels of bacterial bioerosion within the articulated Frälsegården bone specimens were more extensive than what would be expected if putrefaction had been significantly curtailed.

An alternative hypothesis could be that the articulated bodies had been wrapped soon after death, but subsequent interment within the Frälsegården tomb was delayed. Efficient wrapping of the body would have prevented some insects from gaining access to the corpse and so the bones would have been exposed to extensive soft tissue decomposition, despite remaining unburied (Galloway *et al.* 1989; Goff 1992; Aturaliya & Lukasewycz 1999; Campobasso *et al.* 2001; Fielder & Graw 2003; Kelly *et al.* 2009; Vass 2011). A combination of soft tissue loss facilitated by the insects that had penetrated the wrappings and any inhibitory effects of the wrappings themselves could have been responsible for the arrested signatures of extensive bacterial attack. The relative levels of articulation of these bodies suggested that

they had been placed within the tombs before the bodies had fully decomposed (Sjögren 2010). The implication of a delay between death and burial might indicate that the wrapped remains were displayed for a short while.

Preservation of skeletal articulation and inhibition of bacterial bone bioerosion could have been achieved by an inadequate form of mummification (Parker Pearson *et al.* 2005). The results from the Cladh Hallan skeletons and the Derrycashel bog body indicated that sporadic mummification techniques are likely to promote variable levels of histological preservation and anatomical articulation within skeletal remains (Parker Pearson *et al.* 2005; Kelly 2012). Bacterial bioerosion and patterns of disarticulation within the Frälsegården articulated and partially-articulated remains would reflect the efficacy of the mummification method in each case. This interpretation was weakened by the observation that the histological preservation of the articulated remains was no higher than those that were partially-articulated, as it would be expected that patterns of bacterial attack and articulation would both reflect the quality of mummification. The extensive levels of bioerosion observed within the Frälsegården bones has not yet been equalled within remains obtained from mummified bodies (Weinstein *et al.* 1981; Thompson & Cowen 1984; Hess *et al.* 1998).

The remains from Frälsegården did not demonstrate incidences of Wedl tunnelling, despite them having originated from an open environment that might be expected to have encouraged fungal exploitation. This observation did not invalidate the hypotheses that the remains decomposed within the tomb itself, as the appearance of this type of tunnelling is likely to be related to several factors that control the abundance of fungal spores and their access to the internal bone microstructure. The Frälsegården bones demonstrated minor levels of orange staining, but mild to intense levels of orange infiltrations and inclusions. The results from the assemblage as a whole suggested that the staining, inclusions and infiltration formed as a result of interactions with the iron oxides located within the burial soil (Garland 1987; Grupe & Dreses-Werringloer 1993; Schultz 1997; Hollund *et al.* 2012).

8.2.2.4 Whitwell Quarry, Derbyshire, U.K.

All of the bones sampled from the Whitwell Quarry assemblage demonstrated invariably poor levels of histological preservation, which indicated that they had all experienced extensive putrefaction (Bell *et al.* 1996; Jans *et al.* 2004; Nielsen-Marsh *et al.* 2007). All of the bones originated from the disarticulated linear mortuary deposit within the cairn (Vyner & Wall

2011). The results were consistent with these bodies having been buried soon after death (Rodriguez & Bass 1983; 1985; Bell *et al.* 1996; Nielsen-Marsh & Hedges 2000; Jans *et al.* 2004; Nielsen-Marsh *et al.* 2007). Therefore, one possible interpretation of the patterns of bacterial bioerosion within these samples was that all remains were initially buried elsewhere before the disarticulated bones were exhumed and interred within the tomb. However, the histological results from the bones interred within Carsington Pasture Cave, Beeston Tor and Frälsegården had suggested that deposition within caves or tombs produced similar extensive levels of putrefactive bone bioerosion (Goff 1991; Terrell-Nield & MacDonald 1997). It was possible the indoor environment of the cairn had a similar effect as a cave in restricting invertebrate access and ensuring that soft tissue loss was mostly mediated by natural spontaneous decomposition (Goff 1991; Terrell-Nield & MacDonald 1997).

The histological preservation of the bone from Whitwell Quarry was particularly low but still consistent with the preservation of remains obtained from other tomb and cave sites. Only five bones were sampled from Whitwell Quarry and it was possible that they happened to present a slightly skewed sample of possible variation. The simplest explanation for the histological signatures of the Whitwell Quarry remains was that all of the bodies had been interred as fully-fleshed corpses within the linear mortuary deposit and had been disarticulated by successive activity.

There were no incidences of Wedl tunnelling noted within any of the Whitwell Quarry remains. This observation did not significantly affect the taphonomic interpretation of the Whitwell assemblage, as Wedl tunnelling had not occurred consistently within all bone samples from cave or tomb contexts. The Whitwell sample had been attacked more severely by bacteria than the bones from Carsington Pasture Cave and Beeston Tor, and so there was possibly not enough bone protein available in these samples to facilitate fungal exploitation (Jans *et al.* 2004). The Whitwell bones demonstrated weak orange staining and infrequent inclusions and infiltrations. These features were similar to those found within most archaeological bones used in the present study, and probably occurred as a result of interactions between the bone and iron oxides within the burial environment and percolating ground water (Garland 1987; Grupe & Dreses-Werringloer 1993; Schultz 1997).

8.2.3 Neolithic Summary

Most of the Neolithic remains consisted of disarticulated or partially articulated bones that had been deposited within caves or tombs. Most bone samples from all of these contexts consistently demonstrated extensive levels of putrefactive bioerosion that had been arrested at a variably late stage. These results were consistent with the deposition and decomposition of fleshed bodies within these environments (Galloway *et al.* 1989; Goff 1991; Terrell-Nield & MacDonald 1997). Skeletal disarticulation was encouraged by repeated disturbance, manipulation and selective recovery of remains during and after skeletonisation. Variability in bacterial bone bioerosion amongst these remains probably occurred a result of deviations in the accessibility of remains to invertebrates (Galloway *et al.* 1989; Goff 1991; Terrell-Nield & MacDonald 1997). Samples of Neolithic bones were partly responsible for peaks in Later Prehistoric post-neonatal Whole OHI scores of two and five. The bone samples responsible for Whole OHI scores of five tallied with the two specimens from Carsington Pasture cave that were likely to have been taken from dismembered individuals. The peak at Whole OHI scores of zero and two were explained by decomposition of bodies within cave or indoor environments.

8.2.4 Bronze Age

8.2.4.1 Bradley Fen Settlement, Cambridgeshire, U.K.

All three of the skeletons sampled from the Bradley Fen were articulated at the point of recovery yet were allocated high Whole OHI scores of four or five. The sample from Sk 853 was entirely free from microbial bioerosion. High histological preservation was an atypical finding amongst the articulated remains sampled for this project. Less than three-per-cent of the Historical baseline samples demonstrated Whole OHI scores of four or five and less than two-per-cent were free from microbial bioerosion. These patterns of bacterial bioerosion suggested that putrefaction of these remains had been interrupted at an early *post mortem* juncture (Bell *et al.* 1996; Jans *et al.* 2004; Nielsen-Marsh *et al.* 2007; Hollund *et al.* 2012).

Burial 853 was recovered from a watering hole whose base had been positioned strategically below the water table (Knight 2008, personal communication). It was probable that this individual had decomposed within a waterlogged anoxic environment. This skeleton had eventually been buried by accumulations of silt (Knight 2008, personal communication). The

immaculate histological preservation of bone from Burial 853 was best explained by this individual having been deposited within waterlogged anoxic sediments soon after death (Turner-Walker & Jans 2008; Hollund *et al.* 2012). The resultant anoxic environment would have arrested early decomposition and prevented putrefactive bioerosion of the bone (Turner-Walker & Jans 2008; Hollund *et al.* 2012).

The sediments that surrounded Burials 573 and 785 consisted of sandy clay and were not waterlogged (Knight 2008, personal communication). There were no indications that these sediments were or had ever been anoxic, either in terms of the survival or organic material or the composition of the burial soils (Knight 2008, personal communication). These two bodies had been buried shallowly within sediment located two metres above the original ground water level (Appleby 2005). Histological preservation of bones sampled from Historical anoxic deposits were variably elevated. However, the histological preservation of the two remaining Bradley Fen samples were higher than the overall preservation of the anoxic-deposited Historical remains. The intermittent waterlogging associated with the Historical sites meant that some of the remains recovered from these locations had probably decomposed under aerobic conditions. This observation combined with the small number of samples from Bradley Fen meant that it remained uncertain whether the histological signatures of the Bradley Fen bones had been caused by environmental anoxia (Hollund *et al.* 2012). However, the lack of evidence that these skeletons had decomposed within a waterlogged context meant that an anthropogenic explanation for their heightened levels of histological preservation had to be considered.

Rapid skeletonisation associated with sub-aerial exposure of a cadaver reduces the levels of putrefaction that bones experience (Rodriguez & Bass 1983; 1985; Bell *et al.* 1996; Simmons *et al.* 2010; Vass 2011). The correct anatomical articulation of the bones from Burials 573 and 785 precluded the possibility that they had been sub-aerially exposed (Knight 2008, personal communication). Some of the bones of Burial 853 had been modified by rodents (Knight 2008, personal communication). It was possible that this modification had been enacted by burrowing mammals that were able to access the shallow grave, although there were no notable signs of burrowing within the burial sediment (Knight 2008, personal communication). These observations suggested that there may have been a delay between the death and burial of Burial 853 that facilitated rodent access.

Shallow burial might encourage patterns of bodily decomposition similar to those of sub-aerially exposed cadavers because of the higher environmental temperatures and increased

accessibility of the cadaver to skeletonising insects (Rodriguez & Bass 1985; Yoshino *et al.* 1991; Campobasso *et al.* 2001; Dent *et al.* 2004; Vass 2011). Burials 573 and 785 had been buried shallowly, and so this scenario could explain their heightened levels of histological preservation as well as evidence for rodent modification (Yoshino et al 1991). However, forensic studies of decomposition have suggested that different parts of partially-buried bodies decompose differently depending on whether they lie above or below the ground (Schotsmans *et al.* 2011). The results from the Primary Analysis had suggested that burial depth that did not result in anoxia had little effect on bacterial bone bioerosion (Nielsen-Marsh & Hedges 2000; Jans *et al.* 2004; Nielsen-Marsh *et al.* 2007; Smith *et al.* 2007; Turner-Walker 2008).

The flexed postures of the Bradley Fen burials, particularly the highly contorted attitude of Burial 573, suggested that the bodies had been wrapped (Parker Pearson *et al.* 2005; Nilsson Stutz 2006). Coverings have only been observed to interfere substantially with bodily decomposition under particular environmental conditions that augment the effects of wrappings (Galloway *et al.* 1989; Forbes *et al.* 2005; Notter & Stuart 2011; Vass 2011; Ferreira & Cunha 2012). The results from the Primary Analysis had suggested that wrapping or clothing do not significantly affect bacterial bone bioerosion. It was unlikely that wrapping alone would have affected decomposition of the Bradley Fen carcasses in a way that would have significantly curtailed the putrefactive bioerosion of the bone microstructure.

The literature review and analysis of the mummified remains demonstrated that bones from mummified bodies are the only ancient articulated remains that consistently retain high levels of histological preservation (Weinstein *et al.* 1981; Thompson & Cowen 1984; Stout 1986; Brothwell & Bourke 1995; Garland 1995; Hess *et al.* 1998; Parker Pearson *et al.* 2005). The results from the Derrycashel bog body established that bones from mummified remains can experience limited levels of putrefactive bioerosion when they have been preserved using inefficient methods. Previous mummification of the Bradley Fen remains was a plausible explanation for their histological signatures of arrested putrefactive bioerosion. Mummification and curation would also explain the rodent modification of Burial 853.

If the Bradley Fen remains had been intentionally preserved, the levels of bacterial bioerosion within these bones suggested that the technique employed had not arrested putrefaction immediately. These signatures of bioerosion were similar to those found within the bones of the Derrycashel bog body, which suggested that the Bradley Fen remains may have been only partially mummified. These results were similar to those obtained from the Cladh Hallan

skeletons, and may indicate that the Bradley Fen individuals could represent composite bodies (Parker Pearson *et al.* 2005; Hanna *et al.* 2012). The suggestion that Burials 573 and 785 had been mummified before they were buried raised questions as to whether Burial 853 was similarly treated. An identical diagenetic signature would have been produced within the skeleton of Burial 853 had the body been deposited as a fresh or mummified cadaver. The results from the Primary Analysis had suggested that Later Prehistoric treatment was more likely to be responsible for the absence of bacterial bioerosion from archaeological bone than anoxic environment.

The Historical baseline assemblage included a small proportion of remains that demonstrated high levels of histological preservation. It could be argued that the two Bradley Fen specimens represented outliers within the natural variation of bacterial bioerosion caused by immediate burial that had been captured by random chance. This possibility could not be dismissed within the context of the Bradley Fen site. However, based on the Historical baseline distribution, it was improbable that bone samples extracted from two articulated burials across one site would both demonstrate high levels of histological preservation unless there was some other process involved (Jans *et al.* 2004; Nielsen-Marsh *et al.* 2007; Smith *et al.* 2007; Jans 2008; Hollund *et al.* 2012). The best explanation for the patterns of bioerosion observed within the Bradley Fen remains was that they were subject to funerary processes that curtailed their putrefaction and preserved their soft tissues.

All of the Bradley Fen skeletons demonstrated orange staining at their periosteal and endosteal surfaces. This staining was intense within the bones from Burial 573 and 785 and more superficial within the samples from Burial 853. Accumulations of iron oxides within archaeological remains have been associated with initial decomposition under anoxic conditions (Hollund *et al.* 2012). However the distribution of these features within the Bradley Fen remains was consistent with similar phenomenon observed within the majority of the study sample. Their presence within the Bradley Fen specimens could not be taken to be indicative of a decompositional environment that had interfered with putrefactive bone bioerosion (Hollund *et al.* 2012). It was likely that the orange staining had accumulated as a result of interactions between the bone and iron oxides within the burial environment (Garland 1987; Grupe & Dreses-Werringloer 1993; Schultz 1997). The availability of iron oxides within the Bradley Fen burial environment was attested to by the frequent appearance of iron panning on skeletal remains from the site (Appleby 2005).

Anoxic decomposition and subsequent iron oxide formation usually lowers the local pH producing microfissuring within the internal bone microstructure (Turner-Walker 1999; Turner-Walker & Jans 2008; Hollund *et al.* 2012). No such diagenetic alterations were recorded from the Bradley Fen specimens. These features, as well as iron oxide staining, were also mostly absent from the bones of Burial 853 which almost certainly did decompose within an anoxic environment. Perhaps the remains of Burial 853 were never sufficiently aerated to encourage iron oxidation, or the microstructural features associated with anoxic decomposition do not always appear. These results supported the assertion that putrefactive bioerosion within the bones of Burials 573, 785 and possibly 853 was not arrested by environmental conditions.

The bones of Burial 853 demonstrated dark macroscopic staining, yet microscopic analysis revealed that this discolouration was superficial, and had occurred as a result of a thin layer of extraneous dark material that adhered to the cortex. The opacity of this material made it difficult to interpret its constitution, but it was similar to the inclusion that filled the natural bone microporosities. The bones of Burials 573 and 785 were not obviously discoloured on a macroscopic scale, despite demonstrating intense orange microscopic staining to their periosteal surfaces. The intense and intrusive orange staining observed within the bones of Burials 573 and 785 suggested that their burial environment encouraged higher levels of iron oxide infiltration than the sediments that surrounded Burial 853. Iron oxides must have been more abundant within the clay soils of Burials 573 and 785 than within the silts that contained Burial 853. This finding was consistent with variations in orange aesthetic diagenetic changes with burial soil observed amongst the assemblage as a whole.

The dark brown inclusions that were observed within all of the Bradley Fen thin sections were similar in colour and morphology to those found commonly within most of the archaeological remains sampled for the present study (Garland 1987; Grupe & Dreses-Werringloer 1993; Schultz 1997; Hollund *et al.* 2012). It was likely that these inclusions represented deposits of iron oxides that had entered the bone through the movement of percolating groundwater (Garland 1987; Grupe & Dreses-Werringloer 1993; Schultz 1997). The high frequency and intensity of the inclusions found within the Burial 853 thin sections was probably a result of the watery environment having increased the mobility of extraneous materials. Decomposition within anoxic waterlogged environments promotes the formation of framboidal pyrite and so this material may have partially constituted the dark inclusions found within the Burial 853 thin section (Turner-Walker 1999; Turner-Walker & Jans 2008; Hollund *et al.* 2012).

8.2.4.2 Cladh Hallan Settlement, South Uist, U.K.

Parker Pearson *et al.* (2005; 2007) had already published an interpretation of the funerary processes responsible for the signature of bioerosion within CH 2638. They concluded that the limited levels of bacterial bone bioerosion found within this sample were consistent with this skeleton having been previously mummified (Parker Pearson *et al.* 2005). This interpretation was supported by studies of the histological preservation of bone from mummified human individuals included in the present and previous studies (Weinstein *et al.* 1981; Thompson & Cowen 1984; Brothwell & Bourke 1995; Hess *et al.* 1998). The composite CH 2316 skeleton had been subject to similar types of *post mortem* treatment as CH 2638. It was inferred by association that this skeleton had also previously been mummified (Parker Pearson *et al.* 2005).

The finding that CH 2686 was composed of the partially articulated parts of several individuals could infer that this individual was constructed from parts of individuals that had been sub-aerially exposed (Parker Pearson *et al.* 2005; Hanna *et al.* 2012). However, the patterns of articulation amongst the constituent parts of this individual combined with the long period between death and burial inferred by the radiocarbon dates precluded the possibility that this body had been constructed from the remains that had been partially disarticulated through sub-aerial exposure (Micozzi 1991; Parker Pearson *et al.* 2005; Duday 2006).The partial preservation of the mummified remains from Derrycashel was consistent with the partial articulation of the constituent parts of CH 2686, and provided further proof that the haphazard technique of mummification utilised at Cladh Hallan could have involved submersion of the remains within a sphagnum peat bog. There was no indication that the environmental conditions of the *in situ* burial contexts of the Cladh Hallan remains would have promoted anoxic bodily decomposition (Parker Pearson *et al.* 2005).

Summerfield (2004) had also taken samples of bone from the discrete individuals represented by the cranium and the mandible of CH 2868. These bones were not included within the present study because they did not originate from long bones. Both samples were free from bacterial bioerosion or demonstrated only limited bacterial attack (Summerfield 2004). Therefore all of the known separate individuals that constituted the CH 2868 composite demonstrated signatures of bacterial decay that were best explained by the remains having been previously mummified (Weinstein *et al.* 1981; Thompson & Cowen 1984; Stout 1986; Brothwell & Bourke 1995; Garland 1995; Hess *et al.* 1998; Parker Pearson *et al.* 2005).

Histological preservation amongst the rest of the Cladh Hallan human remains was variable (Summerfield 2004). Two samples demonstrated extensive levels of bacterial bioerosion suggesting that they had been exposed to the highest levels of putrefactive bacterial activity. These patterns of bioerosion were consistent with the samples having decomposed as part of corpses that were buried immediately after death (Bell *et al.* 1996; Nielsen-Marsh & Hedges 2000; Jans *et al.* 2004; Nielsen-Marsh *et al.* 2007). One of these samples had been taken from the femur of the skeleton CH 2616. This result was ostensibly inconsistent with this part of the skeleton having originated from a previously-mummified individual, as preservation of the soft tissue is usually achieved through the cessation of putrefaction (Aufderheide 2003; Parker Pearson *et al.* 2005). This result clashed with the taphonomic and dating evidence, which were consistent with mummification (Parker Pearson *et al.* 2005; 2007).

Prior mummification provided the only explanation for the levels of articulation observed amongst the constituent parts of CH 2616. The level of articulation observed amongst these skeletons would be improbable had they been reconstructed out of disarticulated parts of bodies that had decomposed naturally (Micozzi 1991). The ways in which the constituent parts of these bodies were assembled suggested that the inhabitants of Cladh Hallan must have had some anatomical knowledge. However, it seemed unlikely that this knowledge would have extended to the intricate articulations of the bones of the hands and feet, particularly in a way that would have retained the unstable positions observed within the Cladh Hallan skeletons. Patterns of skeletal articulation were more similar to those observed amongst skeletonised remains that were likely to have been formerly mummified (Maureille & Sellier 1996).

The high levels of bacterial bioerosion observed within the femur of CH 2616 might be explained in one of two ways. It was possible that the reconstruction of individuals did not consist only of mummified remains, but included infrequent single or partially articulated bones from bodies that had decomposed naturally whilst buried. The left femur that was sampled from CH 2616 had been manipulated *post mortem*, along with the corresponding tibia and patella (Parker Pearson *et al.* 2005; 2007). The femur of CH 2616 may have originated from an individual that had partially decomposed underground before being disinterred. The partially-decomposed leg could have been incorporated within the composite body after the internal bone microstructure had been bioeroded by putrefactive bacteria. This argument is weakened by the radiocarbon dates from the bone, which suggested that the femur was likely to have been older than its surrounding sediments, although there was a small overlap. The period between death and disinterment would have ensured that the lower limb would have entirely skeletonised and disarticulated.

An alternative hypothesis was that the leg originated from a body that was incompletely mummified. The suggestion that the mummification method adopted at Cladh Hallan was only sporadically successful was evidenced by the composite nature of the whole bodies as well as the arrested patterns of internal putrefactive bioerosion within the sample from CH 2638. If the method of mummification was only sporadically effective, the assembly of mummified parts might have represented the conglomeration of the best-preserved bits of several bodies to produce the most complete individual. Similar attempts to reconstruct single individuals form incompletely-mummified bodies have been observed within assemblages of Greco-Roman mummified human remains from the Dakleh Oasis in Egypt (Aufderheide *et al.* 1999; Aufderheide 2003). Small-angle x-ray analysis of the bones of the CH 2868 sample revealed a level of demineralisation that was most likely caused by the body having been deposited in an acidic environment, such as a bog (Parker Pearson *et al.* 2005). Inconsistent mummification promoted by a bog environment was apparent within the Derrycashel bog body, in both the partial preservation of its soft tissues and bioerosion of the internal bone microstructure (Kelly 2012). The limited level of bacterial bioerosion observed within the tibia of the Derrycashel bog body was comparable to that recorded from Cladh Hallan skeleton CH 2868 (Parker Pearson *et al.* 2005: 541).

The identification of bacterial bioerosion within the bones of the Derrycashel bog body indicated that bone from a mummified individual preserved using an inconsistent method may have experienced putrefactive bioerosion. The results from this sample had also suggested that the occasional loss of the skeleton from preserved bog bodies may be due to the failure of the bog environment in preventing extensive putrefactive bioerosion of the bone. Bog environments that failed to prevent some putrefactive bone bioerosion may still have preserved the superficial soft tissues sufficiently to have ensured some level of skeletal articulation. If all of the formerly-mummified remains from Cladh Hallan had been preserved through deposition in a bog, putrefactive bone bioerosion would have varied between individuals. This scenario would provide an explanation for the extensive levels of bacterial bioerosion observed within the femur from the CH 2616 mummy. A sample taken from a part of the skeleton that represented a different individual may reveal a contrasting signature of bacterial bone bioerosion, more consistent with mummification. The suggestion that the bones of a preserved body may have been variably bioeroded by putrefactive bacteria weakened the potential utility of histological analysis in identifying skeletal remains that had been formerly mummified. Unusually low levels of bacterial bioerosion in bone is likely to a

tendency rather than an absolute within bodies that were mummified using techniques that did not involve evisceration or immediate neutralisation of gut microbiota.

The other bone sample from Cladh Hallan that had been intensely bioeroded was taken from the skeleton of a ten-to-fourteen-year-old child (CH 2727) that had been buried underneath a roundhouse (Parker Pearson *et al.* 2004; 2005). This skeleton retained a tightly flexed posture, but demonstrated no further evidence for unusual treatment. There was no evidence for unusual *post mortem* treatment and the radiocarbon dates from this individual were not anomalously early (Parker Pearson *et al.* 2005). The simplest explanation for the taphonomic and histological evidence was that CH 2727 had been buried underneath the roundhouse soon after death (Summerfield 2004).

The skeleton of the CH 2792 three-year-old child that was also recovered from underneath a roundhouse demonstrated high levels of bacterial bioerosion. However, this attack was not as extensive as what was observed within the previous two specimens. This level of putrefactive bioerosion was observed infrequently within the Historical baseline assemblage, which indicated that this individual may not have been buried immediately after death. This signature of bioerosion was observed most often within cave-deposited remains, or Iron Age samples where there was some evidence that the body had been left to decompose in the open air for a short while. The majority of the CH 2792 skeleton was represented, although most of it was disarticulated, which suggested that the body was in an advanced state of decomposition when it was buried (Parker Pearson at al. 2005). There was no evidence that the grave had been disturbed after burial, and so the disarticulated parts must have been retained within some form of container (Parker Pearson *et al.* 2005).

The histological preservation of this specimen was consistent with retention of the body within a sealed bag or other container for a short while above ground before it was buried. Such a container would have limited access to skeletonising insects and ensured that the bones were exposed to extensive levels of putrefaction. However, radiocarbon dates of the bones of this specimen were appreciably earlier than the dates of the construction of the roundhouse (Parker Pearson *et al.* 2005). It was possible that the decomposing remains had been retained within a container whilst the roundhouse was constructed and buried once building was completed. However, the length of time between the death and deposition indicated by the radiocarbon date stipulated that the body should have completely disarticulated by the time it was interred (Rodriguez & Bass 1983; 1985; Parker Pearson *et al.* 2005). The exact timing of bodily decomposition is highly variable. However, uninhibited bodily decomposition in a

temperate environment, particularly above-ground, would be expected to take no longer than a few years (Rodriguez & Bass 1983; 1985; Janaway 1996; Manhein 1997; Rodriguez 1997; Campobasso *et al.* 2001; Dent *et al.* 2004; Wilson *et al.* 2007; Vass 2011; Fereira & Cunha 2013). The overlap of the radiocarbon dates meant that it was still possible that this specimen had decomposed within an organic container above ground (Parker Pearson *et al.* 2005). However, the partial perseverance of skeletal articulation and limited bacterial bone bioerosion of this specimen was also consistent with a haphazard mummification process (Aufderheide 2003; Lynnerup 2007). Evidence for the preservative treatment of other individuals from the Cladh Hallan site may circumstantially support similar conclusions regarding the partial articulation of CH 2792. The histological preservation of CH 2792 was too low to be undoubtedly attributed to mummification.

The unstratified disarticulated femur that was uncovered from a separate part of the site during quarrying activities was the only bone sample from Cladh Hallan that remained free from microbial bioerosion. This bone had not been exposed to bodily putrefaction. It was not clear whether this bone represented part of an articulated burial or a disarticulated deposit (Summerfield 2004). Disarticulation via surface exposure would have limited the level of putrefactive decay that the bone experienced (Bell *et al.* 1996; Fernández-Jalvo *et al.* 2010; Simmons *et al.* 2010). However, only a few bones from surface-exposed cadavers remain free from microbial bioerosion and it is likely that most will have been exposed to limited putrefaction (Bell *et al.* 1996; Fernández-Jalvo *et al.* 2010; Simmons *et al.* 2010). Another possible explanation was that the body that this femur belonged to had originally been purposefully dismembered or defleshed soon after death (Jans *et al.* 2004). No tool marks were located on this bone, although dismemberment could have been performed without producing marks (Guilday *et al.* 1962; Binford 1981; Fisher 1995).

The immaculate histological preservation of this CH-C sample was also consistent with prior mummification (Weinstein *et al.* 1981; Thompson & Cowen 1984; Stout 1986; Brothwell & Bourke 1995; Garland 1995; Hess *et al.* 1998). This scenario was pertinent when the other potential disarticulated formerly-mummified remains from this site were considered. The lack of bacterial bioerosion to the internal bone microstructure of this specimen suggested that the cessation of putrefaction had been more successful than within the bodies of CH 2616 and CH 2868. The lack of context for this specimen was frustrating, as it could not be established whether it originated from a fully-articulated mummified individual or another reconstructed composite.

A small number of articulated bones sampled from the Historical baseline assemblage were free from bioerosion, and it was possible that the abnormal histological signatures located within the remains from Cladh Hallan represented a skewed sample of natural variation. However, the accompanying dating and taphonomic evidence combined with the high levels of histological preservation observed within the remains that composed CH 2868 suggested that it was improbable that the diagenetic signatures were a result of skewed natural variation within bodies that had been buried soon after death (Parker Pearson *et al.* 2005; 2007). Most of the bone samples from Cladh Hallan demonstrated superficial levels of orange and yellow staining and infrequent inclusions and infiltrations. The nature of all these features were consistent with those that appeared commonly within most of the archaeological bones sampled for this study. These features were most likely to represent interactions between the bone and iron oxides within the soil and the percolating groundwater (Garland 1987; Grupe & Dreses-Werringloer 1993; Schultz 1997). The mildness of these visual diagenetic changes most likely attested to the paucity of iron oxides within the machair sand burial environment and was inconsistent with these diagenetic features having formed as a result of bodily decomposition within an anoxic environment (Hollund *et al.* 2012).

None of the Cladh Hallan bone samples demonstrated characteristic microstructural staining, inclusions and infiltrations that would have been indicative of previous deposition within a bog (Garland 1995). Studies of changes to bone and soft tissues placed within sphagnum bogs have demonstrated that bones deposited in direct contact with the bog are subject to only mild staining within the time it takes for soft tissue to mummify (Gill-Robinson 1999; Turner-Walker & Peacock 2008). The intense red staining observed within the Derrycashel sample was the result of the body having been deposited within the bog environment for millennia (Garland 1995). It was likely that the mild bone staining that may have been acquired by the bone while the Cladh Hallan body was in a bog would have been replaced by discolouration promoted by elements within the new burial soils. Any remains of sphagnum or algae desmids that had managed to infiltrate the Cladh Hallan bones may also have been replaced by factors intrinsic to the new burial soils (Garland 1995).

8.2.4.3 Cnip Headland Cemetery, Isle of Lewis, U.K.

All but one of the bone samples from Cnip were entirely free from bioerosion, which suggested that they had been treated in a way which prevented their exposure to putrefactive bacteria.

Disparate skeletal elements from discrete individuals had been sampled from Cnip. However, the results from the whole assemblage, the supplementary samples and the Cnip remains taken in isolation suggested that bacterial bioerosion did not vary significantly with skeletal element.

One of the samples that was free from bacterial bioerosion had come from a neonatal individual (Sk. 3) that was recovered within a grave located underneath an adult female skeleton (Sk. 2) in Area D (Knott 2010). The neonatal skeleton was partially disturbed when the adult female body was inserted (Knott 2010). The nature of the skeletal disarticulation of the neonate suggested that this disturbance had taken place after the neonatal body had decomposed. The best explanation for the histological preservation of the neonatal individual was that it had been stillborn, or died soon after birth.

The sample from the adult female skeleton that directly overlay the neonatal remains (Sk. 2) was the only one from Cnip that had been bioeroded (Knott 2010). This specimen had been exposed to high levels of putrefactive attack. There was a severe contrast in the level of bioerosion observed within this specimen and the sample from the neonatal skeleton that lay directly beneath it, which reinforced the notion that bacterial attack was not a consequence of the burial environment. The signature of bioerosion within Sk. 2 was consistent with the body having been buried intact soon after death (Rodriguez & Bass 1983; 1985; Bell *et al.* 1996; Jans *et al.* 2004; Nielsen-Marsh *et al.* 2007). This skeleton had demonstrated a certain degree of skeletal disarticulation when it was uncovered, which suggested that the grave may not have represented the primary depositional context (Knott 2010). However, the disarticulation of this skeleton was slight and could have occurred as a result of movement during decomposition.

All of the disarticulated and partially articulated bones sampled from Areas A and C were free from microbial bioerosion. The radiocarbon dates of bone from all contexts were statistically indistinguishable (Lelong 2011, personal communication). The most direct way that putrefactive bioerosion within these remains could have been prevented was through dismemberment or defleshing (Jans *et al.* 2004; Nielsen-Marsh *et al.* 2007). No cut marks were identified on any of the remains recovered from Cnip Areas C and A, although this type of processing may not have left marks on the bone (Guilday *et al.* 1962; Binford 1981; Fisher 1995). It was unlikely that the body from the Area A cist had been dismembered, as the skeleton was fairly complete and most of the bones lay in anatomical articulation (Lelong 2011). The impression of correct skeletal articulation observed within some of the remains from the Cnip may have been distorted by attempts at skeletal reassembly (Lelong 2011).

However, the level of skeletal articulation within Sk. 1 from the Area A cist was unlikely to have been achieved through reassembly of entirely disarticulated elements. Accurate reassembly of skeletal form was not considered necessary for most of the disarticulated remains from Area C.

Sub-aerial exposure of the remains would have ensured that putrefactive bacterial bioerosion was kept to a minimum whilst promoting swift disarticulation (Rodriguez & Bass 1983; 1985; Bell *et al.* 1996; Fernández-Jalvo *et al.* 2010; Simmons *et al.* 2010). Redfern (2008) and Carr & Knüsel (1997) reasoned that remains excarnated by sub-aerial exposure would demonstrate some evidence for carnivore scavenging and weathering. No carnivore marks were located on any of the Cnip remains, although the exposed bodies may have been protected from these factors by a barrier or deposition on an elevated platform. The cortex of the bones samples from Cnip had been badly eroded, although it was unclear whether this represented the kind of weathering that occurs as a result of sub-aerial exposure (Lelong 2011). The bones of the adult skeleton from Area D demonstrated the highest levels of cortical weathering, despite the probability that this individual had decomposed below ground (Lelong 2011).

The sporadic articulation of the remains from Areas A and C suggested that they had been retrieved and buried before the soft tissues had fully decomposed. It was unlikely that the bare bones had been left to weather for a significant length of time. Bones of sub-aerially exposed bodies experience some putrefaction (Bell *et al.* 1996; Turner-Walker & Jans 2008; Fernández-Jalvo *et al.* 2010; Hollund *et al.* 2012). The absence of bacterial tunnelling from the Cnip samples, whilst consistent with surface exposure, would represent an unusual finding within bones from bodies that were treated in this fashion (Bell *et al.* 1996; Turner-Walker & Jans 2008; Fernández-Jalvo *et al.* 2010; Hollund *et al.* 2012).

The consistent levels of microstructural preservation observed within the Cnip samples could be explained by sub-aerial exposure had they all been afforded this treatment at the same time of year. The results from the Historical baseline distribution established that seasonality had not significantly affected putrefactive bone bioerosion within buried remains at sites where it had no effect on intermittent waterlogging. However, must forensic investigations of decomposition that established links between seasonality and cadaveric decomposition studied unburied bodies (Rodriguez & Bass 1984; 1985; Mann *et al.* 1990; Bass 1997; Campobasso *et al.* 2001; Vass 2011). Unlike buried samples, seasonality will affect the extent as well as the rate of putrefaction that the bones are exposed to because of the associated abundance of skeletonising insects (Rodriguez & Bass 1983; 1985; Campobasso *et al.* 2001; Simmons *et al.* 2010; Vass 2011). Increased insect activity would have severely limited the

levels of soft tissue putrefaction experienced by bones (Rodriguez & Bass 1983; 1985; Galloway *et al.* 1989; Simmons *et al.* 2010). Therefore, it was feasible that sub-aerial exposure could explain patterns of bioerosion and disarticulation within the Area A and C samples had all of the remains been originally exposed during warmer months.

Variation in levels of articulation amongst the Area A & C bones indicated that there must have been discrepancies in the time that each individual represented at Cnip had been sub-aerially exposed (Lelong 2011). The limited skeletal disarticulation observed within the skeleton from the Area A cist suggested that this body must have decomposed for a shorter period of time than the individuals represented by the largely disarticulated remains recovered from Area C. Variation in levels of skeletal articulation amongst the remains from Area C supported similar conclusions regarding the variable durations of sub-aerial exposure. The purported link between putrefaction and bone bioerosion suggested that variation in the duration of sub-aerial exposure should have produced disparities in the extent of putrefaction experienced by the bones (Jans *et al.* 2004). A previous study of bacterial bioerosion in bones of fallen livestock suggested that this type of degradation is not influenced by seasonality, even amongst sub-aerially exposed carcasses (Fernández-Jalvo *et al.* 2010). The consistent lack of bacterial bioerosion within the variably-articulated Cnip Area A & C remains meant that sub-aerial exposure did not provide a satisfactory explanation for their disarticulation.

The Cnip Areas A and C remains had not been recovered from their primary depositional context (Lelong 2011). Primary deposition of these remains within an anoxic environment soon after death would have provided one method of prohibiting putrefactive bioerosion of these bones (Hollund *et al.* 2012). This environment must have been consistently anaerobic from the point of deposition in order for it to have inhibited putrefaction consistently (Hollund *et al.* 2012). It was unlikely that the machair sands from which the Cnip bones were all excavated were intrinsically anaerobic, or were frequently rendered so by waterlogging. This notion was supported to by the high level of bacterial bioerosion within the articulated skeleton from Area D (Knott 2010). Another possibility was that all of the individuals represented by the remains from Areas A and C were eviscerated or exsanguinated soon after death.

Initial deposition within an anoxic environment, evisceration, or possibly exsanguination are all processes that are likely to increase the potential for mummification (Aufderheide 2003). Histomorphological studies of bones from mummified individuals have indicated that immaculate preservation of bone histology is more consistent with mummification than excarnation (Weinstein *et al.* 1981; Thompson & Cowen 1984; Stout 1986; Brothwell & Bourke

1995; Garland 1995; Hess *et al.* 1998; Parker Pearson *et al.* 2005; Turner-Walker & Jans 2008; Fernández-Jalvo *et al.* 2010; Hollund *et al.* 2012). As long as the mummification method used was consistent or involved evisceration, prior mummification would best explain the consistent absence of bacterial bioerosion from the Cnip bone samples (Weinstein *et al.* 1981; Thompson & Cowen 1984; Stout 1986; Brothwell & Bourke 1995; Garland 1995; Hess *et al.* 1998; Parker Pearson *et al.* 2005). The disarticulation of the remains from Cnip may contradict an interpretation of mummification, although the evidence from Cladh Hallan suggested that partial disarticulation of Bronze Age mummies may have been the norm (Parker Pearson *et al.* 2005; 2007). The attempts at skeletal reassembly within some of the remains from Area C provided conjectural parallels between the Cladh Hallan and Cnip assemblages (Lelong 2010). It was conceivable that the Cnip Areas A and C were repositories for partially articulated mummified material.

The radiocarbon dates obtained from the bones from Areas A & C were slightly earlier than those from Sk 2, although overall the dates were not significantly different (Lelong 2011, personal communication). The discrepancy in the dates would be consistent with the remains from Area A & C having been curated for a certain length of time before the death and burial of Sk. 2. It was possible that the interment of all these remains occurred at the same time, despite their variable dates of death. However, the radiocarbon dates of these individuals were so close that they would also be consistent with a scenario that involved sub-aerial exposure rather than mummification.

Several of the well-preserved samples from Cnip demonstrated a reduced level of birefringence that was coincident with brown microstructural staining. It was likely that the loss of collagen birefringence in these samples did not represent loss of protein, but interference from microstructural staining (Hackett 1981; Garland 1987; Turner-Walker 2008). The orange inclusions that were observed infrequently within the Cnip samples were similar to the type that were found commonly within most archaeological remains sampled for the current study. These features were likely to represent deposits of iron oxides that had precipitated out of percolating groundwater (Garland 1987; Grupe & Dreses-Werringloer 1993; Schultz 1997). The absence of orange staining within this sample set suggested that the infrequency of inclusions was probably attributable to a lack of iron oxides present within the sandy burial environment.

Brown staining was observed in the thin sections taken from the right radius and a left femur excavated from Area C. Brown staining was also present within the burial sediment that

surrounded these remains. It was likely that both phenomena were caused by organic material that had accompanied the remains and subsequently decomposed (Garland 1987; Grupe & Dreses-Werringloer 1993; Schultz 1997). Decayed soft tissue does not normally leave a visible mark in the burial sediment. Such marks occur more commonly where durable organic materials, such as wood, leather or wicker, have slowly been degraded within the grave (Janaway 1996). The excavators believed that the staining that surrounded the disarticulated Cnip remains represented decayed soft tissue (Knott 2010; Lelong 2011). However, similar staining found surrounding the neonatal skeleton from Area D was interpreted as evidence for the former presence of a durable organic material that had been used to contain the body (Knott 2010).

The presence of staining suggestive of treated organic tissue in the areas surrounding the disarticulated bones from Cnip might be salient with regards to the mummification hypothesis. However this brown staining was not found around all bones recovered from the site. Perhaps some of the remains from Area C had originally been placed in organic containers, or the specific environment of these bones promoted the retention of decomposition products produced by soft tissues. There was no suggestion that humic acids had arrested osteolytic decomposition through the deactivation of bacterial collagenase (Hedges 2002; Jans *et al.* 2004). Histological bone preservation persisted in areas that did and did not demonstrate brown staining.

8.2.4.4 Ingleby Barwick Cemetery, County Durham, U.K.

Two bone samples from Ingleby Barwick were free from bone bioerosion and two had been extensively bioeroded. When combined with the *in situ* states of articulation of these remains, the histological results suggested that there were possibly three separate funerary rituals represented at the site. The poor microstructural preservation and correct skeletal articulation of the Sk. 5 and Sk. 6 samples were consistent with immediate burial (Annis *et al.* 1997). The excellent microstructural preservation of the bone from the earlier Sk. 2 and Sk. 3 specimens suggested that they had been manipulated in a way that prevented their exposure to endogenous putrefying bacteria (Bell *et al.* 1996; Jans *et al.* 2004; Nielsen-Marsh *et al.* 2007).

The absence of bacterial tunnelling from within the ostensibly Neolithic disarticulated bones of Sk. 3 suggested that this individual had been excarnated by sub-aerial exposure or dismemberment before the remains were placed within the mortuary box (Bell *et al.* 1996;

Annis *et al.* 1997; Jans *et al.* 2004; Fernández-Jalvo *et al.* 2010; Hollund *et al.* 2012). No tool marks were found on any of the bones recovered from the mortuary box, although dismemberment may not have left any such features (Guilday *et al.* 1962; Binford 1981; Fisher 1995). Rapid skeletonisation associated with sub-aerial exposure would have ensured that the bones were subject to only limited levels of putrefactive bioerosion, although most bones from bodies deposited in this way are exposed to a limited level of putrefactive bacteria (Bell *et al.* 1996; Fernández-Jalvo *et al.* 2010; Hollund *et al.* 2012). Features associated with sub-aerial exposure, such as weathering and carnivore alteration of the bone cortex were absent from the cist remains (Annis *et al.* 1997). The appearance of these features would have been dependent upon the timescale of excarnation and any protection afforded to decomposing remains.

It was more difficult to determine the taphonomic event that prevented putrefactive bioerosion of the articulated Early Bronze Age Sk. 2 specimen (Annis *et al.* 1997). There was no suggestion that the burial sediment was anoxic. The variation in bacterial bioerosion across the site assemblage in spite of the bodies having been buried within a few metres of one another within similar sediment, precluded this possibility (Annis *et al.* 1997). Conventional explanations for the absence of bacterial bioerosion within this specimen such as dismemberment or excarnation could not be applicable due to the skeleton's correct anatomical articulation. This body must have been treated in a manner that prevented bacterial bioerosion but promoted skeletal articulation. The results from the Historical remains had suggested that bacterial attack can remain uninitiated within a small proportion of bones from bodies that were buried soon after death. However, the chance of encountering such a sample were low.

The patterns of articulation and bacterial bioerosion of the Sk. 2 bones were consistent with mummification or evisceration (Weinstein *et al.* 1981; Thompson & Cowen 1984; Stout 1986; Brothwell & Bourke 1995; Garland 1995; Hess *et al.* 1998; Parker Pearson *et al.* 2005). Immediate evisceration would have removed the source of the endogenous bacteria, which would have adversely affected putrefaction and probably stimulated some soft tissue preservation (Aufderheide 2003). Sk. 1 and Sk. 7 were not sampled for thin sectioning, but their radiocarbon dates and burial style were very similar to Sk. 2, and so it could be inferred by association that these bodies may also have been mummified (Annis *et al.* 1997).

The initial analysis of the radiocarbon dates and specific treatments of the individuals buried at Ingleby Barwick had identified three periods of deposition; Late Neolithic interment of

disarticulated bones within the mortuary chamber, Early Bronze Age unfurnished burials and Middle Bronze Age furnished burials (Annis *et al.* 1997). However, Bayesian analysis of the dates indicated that the individuals represented by the bones from the mortuary chamber and the unfurnished burials had died around the same time (Rowe 2012, personal communication). The bones of Sk. 3 had been classified as Neolithic throughout the initial analysis. The high histological preservation of the Sk. 3 bones was similar to what was observed within the contemporaneous remains from the unfurnished Sk. 2 burial and more consistent with mummification than sub-aerial exposure (Weinstein *et al.* 1981; Thompson & Cowen 1984; Stout 1986; Brothwell & Bourke 1995; Garland 1995; Bell *et al.* 1996; Parker Pearson *et al.* 2005; Hess *et al.* 1998; Fernández-Jalvo *et al.* 2010; Hollund *et al.* 2012). When the disarticulated and potentially mummified partially articulated remains from Bronze Age Cnip and Cladh Hallan were considered, another possible interpretation of the cist-deposited remains was that they represented the interment of disarticulated mummified elements.

The disarticulation of the remains from the wooden cist suggested that regardless of whether these remains had been mummified, the bones from individuals that had died in the Early Bronze Age had been curated. Curation would have ensured that date of death and deposition would not necessarily have coincided. Therefore, there may have only been one Middle Bronze Age phase of deposition at Ingleby Barwick that involved curated remains being buried alongside fresh furnished cadavers. The presence of disarticulated human material within the grave of Sk. 6 provided circumstantial evidence that contemporaneous deposition of curated and fresh remains had been practised at Ingleby Barwick (Annis *et al.* 1997).

All of the remains from Ingleby Barwick contained orange inclusions that were found typically within most of the study sample. These features were likely to represent deposits of iron oxides (Garland 1987; Grupe & Dreses-Werringloer 1993; Schultz 1997). None of the remains demonstrated significant orange staining, which suggested that iron oxides were not prevalent within the surrounding environment. Brown staining was identified within bones from Sk. 2 and Sk. 3. This staining was similar to that observed within the remains recovered from the Cnip Headland, although no brown staining was identified within the surrounding burial context. Brown staining was most intense within the disarticulated remains from the cist. The results of the current and previous studies indicated that brown staining is associated with the release of humic acids from decaying organic matter (Garland 1987; Grupe & Dreses-Werringloer 1993; Schultz 1997). The presence of humic factors within the burial context of Sk. 3 would be logical given that these remains had been surrounded by a wooden cist (Annis *et al.* 1997). No traces of organic remains were located from within the grave of Sk. 2, although

staining of this individual was less severe than what was observed within Sk. 3. There was no suggestion that humic acids had arrested osteolytic decomposition through the deactivation of bacterial collagenase (Hedges 2002; Jans *et al.* 2004). Histological bone preservation persisted in areas that did and did not demonstrate brown staining.

8.2.4.5 Langwell Farm Cist, Sutherland, U.K.

The Langwell cist specimen was free from microbial bioerosion. This result was obtained rarely from articulated specimens sampled for the present study. Putrefaction of the Langwell body must have been arrested at an early *post mortem* stage in a way that allowed skeletal articulation to be retained. Evidence from the sediments, the cist walls and the survival of organic grave goods suggested that the Langwell cist had been intermittently waterlogged from an early *post mortem* juncture (Lelong 2012). The cist was located close to the banks of the River Oykel. Seasonal changes to the level of this river were likely to be responsible for waterlogging (Lelong 2012). The survival of perishable goods indicated that waterlogging must have occurred frequently within the first few decades after deposition. Complete submersion of the body would have produced an anoxic environment that inhibited putrefaction and bacterial bone bioerosion (Janaway 1996; Turner & Wiltshire 1999; Turner-Walker & Jans 2008; Hollund *et al.* 2012). The inhibitory effects of waterlogging may have been augmented by the presence of the heavy cattle hide wrapping (Mant 1987; Mann *et al.* 1990; Goff 1992; Aturaliya & Lukasewycz 1999; Campobasso *et al.* 2001; Fielder & Graw 2003; Kelly *et al.* 2009; Fereira & Cunha 2013).

The presence of adipocere within the burial environment of the Langwell cist would have provided some credence to the possibility that wrapping combined with waterlogging was responsible for the absence of bacterial bioerosion from the Langwell thin sections. Adipocere degrades more quickly within aerobic conditions, and so it might be expected that conditions which promoted the survival of organic grave goods would also have encouraged the perseverance of adipocere (Fielder & Graw 2003; Forbes *et al.* 2005). White material resembling adipocere was found in abundance within the silhouette of the Langwell body, but chemical analysis of this substance indicated that it was not adipocere (Lelong 2012). Chemical signatures indicative of decomposition products were detected in the soils underneath the Langwell skeleton, but it was unclear whether these signals were diagnostic of adipocere (Lelong 2012). The cist was not waterlogged at the point of recovery, and it was possible that

the frequent oxygenation of the environment following drops in the water level would have perpetuated the breakdown of hydrogenated adipose tissue (Fielder & Graw 2003; Forbes *et al.* 2005).

If putrefaction of the Langwell individual had been affected by waterlogging, the histological preservation of its bones would still represent a relatively rare outcome for bones deposited within conditions that had been intermittently rendered anoxic. The majority of bone excavated from periodically waterlogged environments demonstrated elevated levels of histological preservation, rather than a complete absence of bacterial bioerosion. Only bones from bodies that had been placed directly within contexts that were intrinsically anoxic remain free from bacterial bioerosion (Turner-Walker & Jans 2008; Hollund *et al.* 2012). The cist at Langwell must have been waterlogged soon after deposition if this process was to explain the absence of bacterial bioerosion from the bone microstructure (Hollund *et al.* 2012).

The earliest that non-Wedl MFD have been observed to appear within bone is three moths *post mortem*, and so the contents of the cist must have been rendered anoxic within this time period (Bell *et al.* 1996; White 2009). The persistence of organic grave goods within the Langwell cist suggested that the cist was waterlogged at an early stage. However, the cadaver would have decomposed more quickly than the grave goods and so the survival of the latter did not guarantee that the cist was waterlogged early enough to have affected putrefaction of the Langwell individual. The practicalities of building a cist and interring a body within waterlogged sediment meant that it implausible that the grave was waterlogged when the individual was interred. The body was placed on the ground surface of the cist rather than buried, and so if the cist had been waterlogged in a way that would have affected bodily decomposition, the remains would have had to have been deposited directly within standing water. It was likely that the cist became waterlogged after the body had been deposited, but there was no way of establishing whether this event occurred in time to arrest putrefactive bioerosion of bone. The perseverance of soft tissue or adipocere into the archaeological record would have proven that the cist was waterlogged soon after the body was deposited, although its absence could not be used to argue the opposite (Lelong 2012).

Later Prehistoric treatment was more often responsible for the absence of bacterial bioerosion from bone samples than anoxic environments amongst the whole study sample. The histological signature of the Langwell cist individual was more consistent with bone from mummified individuals rather than the remains recovered from anoxic environments (Weinstein *et al.* 1981; Thompson & Cowen 1984; Stout 1986; Brothwell & Bourke 1995;

Garland 1995;; Hess *et al.* 1998; Parker Pearson *et al.* 2005; Turner-Walker & Jans 2008; Hollund *et al.* 2012). If the Langwell remains had been mummified, the technique efficiently compromised the visceral bacteria soon after death. This level of histological preservation would also be theoretically consistent with evisceration, although this process in itself would have increased the chances of soft tissue preservation (Aufderheide 2003). The same diagenetic signature would have been produced had a mummified individual been deposited within a cist that was later waterlogged. Mummification would explain the slightly anomalous early radiocarbon date that was obtained from this specimen (Lelong 2012). The contrasting radiocarbon dates that were obtained from different parts of this skeleton had suggested to the excavators that the Langwell skeleton might have represented a composite body (Lelong 2012). This observation circumstantially linked the remains to the formerly-mummified remains that were retrieved from Bronze Age Cladh Hallan.

Orange inclusions of the type that were found within most archaeological remains used in the current study were found infrequently within the thin sections of the Langwell individual. These features most likely represented precipitations of iron oxides from percolating groundwater (Garland 1987; Grupe & Dreses-Werringloer 1993; Schultz 1997; Hollund *et al.* 2012). No orange staining was found within this bone. This result was predictable given that these bones had not laid in contact with sediment for a significant length of time. Despite this body having most likely decomposed under anoxic conditions, there was no evidence for localised orange iron oxide staining or framboidal inclusions (Turner-Walker & Jans 2008; Hollund *et al.* 2012). This observation supported the notion that these features are not always present within bone from bodies that decomposed in anaerobic environments (Hollund *et al.* 2012).

The Langwell bone samples demonstrated intense brown staining of the type that is thought to be caused by humic acids produced by decaying organic matter (van Klinken & Hedges 1995; Shahack-Gross *et al.* 1997). The Langwell skeleton was surrounded by a cow hide and a number of partially decayed organic grave goods (Lelong 2012). The presence of brown staining within the Langwell sample reinforced the notion that this type of bone discolouration occurs as a result of the mobilisation of decaying organic matter in the burial environment (Garland 1987; Grupe & Dreses-Werringloer 1993; Schultz 1997). There was no suggestion that humic acids had arrested osteolytic decomposition through the deactivation of bacterial collagenase (Hedges 2002; Jans *et al.* 2004). Histological bone preservation persisted in areas that did and did not demonstrate brown staining.

8.2.4.6 Neat's Court Round Barrow, Kent, U.K.

The histological signatures of the Neat's Court remains formed a bimodal pattern. Three of the bones sampled demonstrated high levels of microstructural preservation, which suggested that they had been treated in ways that exposed the bones to limited levels of putrefactive bioerosion. The other four bone samples had all been extensively bioeroded by bacteria. All of the well-preserved specimens had been recovered in articulation. Their low levels of microbial bioerosion were atypical when compared with the results from the Historical baseline assemblage. A small proportion of the Historical baseline assemblage demonstrated high levels of histological preservation, but this variation was unlikely to account for the proportion of remains from Neat's Court that demonstrated these signatures. These remains must have been treated using a method that limited putrefactive attack to the bone but maintained skeletal articulation (Bell *et al.* 1996; Jan *et al.* 2004; Nielsen-Marsh *et al.* 2007).

The burial soil at Neat's Court consisted of London clay; a very dense marine sediment that may be intrinsically anoxic in its pure form (Morley 2011, personal communication). Archaeological bones recovered from similar marine clays have demonstrated high levels of histological preservation (Hollund *et al.* 2012). However, the burials from this example lay within the waterlogged capillary zone of the water table (Hollund *et al.* 2012). The histologically well-preserved Neat's Court skeletons had been interred within the extension of the primary round mound, which consisted of a mixture of reworked London Clay and domestic waste (Morley 2011, personal communication). The remains had not been buried within the pure clay matrix, and so it was uncertain whether this burial environment would have been intrinsically anoxic. The position of the skeletons within the built-up mound meant that they lay above the capillary zone of the water table. The mound was eventually inundated by tidal incursions that would have induced an anaerobic burial environment (Morley 2011, personal communication). However, palaeoenvironmental evidence and dating of the marine silts suggested that this inundation did not take place until the Late Bronze Age/Early Iron Age, long after the Middle Bronze Age remains would have decomposed (Rodriguez & Bass 1983; 1985; Morley 2011, personal communication).

The probability that the histological structure of the Neat's Court skeleton had been preserved through interment within anoxic sediment was further reduced when the positions of the histologically poorly-preserved remains were considered. The burial context of all but one of extensively bioeroded skeletons consisted of the same material that surrounded the histologically well-preserved remains. These results indicated that the reworked London clay

sediments had not interfered with putrefactive bone bioerosion. All of the skeletons were recovered from similar levels within the ground. There were no differences in burial depth that may have affected the aeration of each grave (Morley 2012, personal communication). Sk. 2673 was buried within the same part of the mound as the three histologically well-preserved skeletons (Morley 2011, personal communication). These four skeletons were buried at similar depths within a few metres of one another. The discrepancy between the bacterial bioerosion of these remains further suggested that the burial sediment had not interfered with bodily decomposition. The bimodal microstructural preservation of the Neat's Court remains was not consistent with samples of bone obtained from intermittently-waterlogged Historical deposits, which demonstrated the full spectrum of histological preservation.

There was no satisfactory environmental explanation for the limited bacterial bioerosion observed amongst the remains from Neat's Court. Anthropogenic interpretations had to be employed. Most methods of treatment that would have limited the bone exposure to putrefaction, such as sub-aerial exposure or dismemberment, would have encouraged the rapid disarticulation of the skeleton (Bell *et al.* 1996; Fernández-Jalvo *et al.* 2010; Hollund *et al.* 2012). The only bones from articulated individuals that consistently demonstrated limited or no levels of bacterial bioerosion are those sampled from mummified remains (Weinstein *et al.* 1981; Thompson & Cowen 1984; Stout 1986; Brothwell & Bourke 1995; Hess *et al.* 1998; Parker Pearson *et al.* 2005). The best explanation for the histological preservation of the well-preserved remains from Neat's Court was that their putrefaction had been arrested through mummification or evisceration. The presence of bacterial bioerosion within the two of the well-preserved samples suggested that evisceration was unlikely to have been involved (Aufderheide 2003; Parker Pearson *et al.* 2007). The signatures of bacterial bioerosion resembled those from the Derrycashel and Cladh Hallan remains, which suggested that the mode of mummification was inconsistent and exposed the bones to minor levels of putrefactive attack (Parker Pearson *et al.* 2005).

Most of the remains from Neat's Court did not demonstrate evidence for unusual *post mortem* treatment beyond the signs of burning (Parker Pearson *et al.* 2005; 2007). However, the articulated skull of one of the putatively mummified skeletons, Sk. 2611, had been displaced from the body, and lay in an unusual position over the right shoulder of the skeleton a few centimetres away from the vertebrae. The articulation of the mandible suggested that the skull had been displaced in the early *post mortem* period and that this displacement had not occurred as a result of the insertion of the medieval drainage pipe that was responsible for the disarticulation of part of the torso (Micozzi 1986; 1991; Duday 2006). The cervical vertebrae

are amongst the first bones to disarticulate via natural decomposition and it was possible that movement of the skull had occurred after the regular loss of soft tissue (Micozzi 1986; 1991; Duday 2006). However significant movement of the skull within the burial environment via decomposition was unlikely, given that the body was surrounded by dense sediment. The atlas and axis vertebrae were the only bones of the spinal column that were absent. This evidence suggested that the skull and mandible may have been removed before the body was buried. It was possible that the body had been decapitated, although no signs of trauma were found on any of the vertebrae or the mandible (Mays 1998: 175). Decapitation would explain damage to but not the loss of the two cervical vertebrae (Mays 1998: 175). If this body had been mummified, than the inefficient system of preservation may have led to the disarticulation of the head at the axis vertebrae. Further deterioration of the head could have led to the loss of the axis and atlas vertebrae before the body and head were buried together.

The rest of the remains from Neat's Court demonstrated extensive patterns of bacterial bioerosion that were consistent with prolonged putrefaction associated with immediate intact burial (Rodriguez & Bass 1983; 1985; Mant 1987; Manhein 1997; Rodriguez 1997; Nielsen-Marsh & Hedges 2000; Jans *et al.* 2004; Nielsen-Marsh *et al.* 2007). The heavily-bioeroded remains included an incomplete skeleton that was recovered in partial articulation. The scattered nature of the bones of this burial had suggested that it represented an articulated skeleton that had been disturbed by later ploughing (Morley 2011, personal communication). The results of the histological analysis supported this conclusion.

Discolouration of the bones and teeth of some of the remains excavated from Neat's Court had been interpreted as the remains having been subjected to unusual *post mortem* treatment involving exposure to heat (Deter & Barrett 2009). Some of the skeletons were surrounded by charcoal within their graves, although there were no signs of *in situ* burning (Morley 2011, personal communication). The burnt remains had not been exposed to heat within or around the burial context, as would be expected had they been subject to an alternative cremation rite such as a *bustum* burial (Dodwell 2012). Signs of heat treatment were found on all of the bones that demonstrated high levels of histological preservation, plus one extra sample that had been extensively bioeroded (Deter & Barrett 2009). These results suggested that heat treatment and histological preservation of the remains may have been linked.

It was difficult to determine whether there were any microstructural indications that the bones from Neat's Court had been exposed to heat (Shahack-Gross *et al.* 1997; Hanson & Cain 2007). Exposure to low temperatures can produce specific alterations to the bone

microstructure (Forbes 1941; Shahack-Gross *et al.* 1997; Hanson & Cain 2007; Squires *et al.* 2011; Castillo *et al.* 2013). Unfortunately these changes usually involve discolouration of the internal bone microstructure that are difficult to differentiate from staining and infiltration by external minerals (Shahack-Gross *et al.* 1997; Hanson & Cain 2007). The abundance of orange staining and infiltrations within the Neat's Court remains meant that it was impossible to determine whether any of these features were indicative of heat-related changes. One osteon within the microstructure of Sk. 2614 demonstrated black infiltrations and characteristic microcracking that could have occurred as a result of heat treatment (Shahack-Gross *et al.* 1997; Hanson & Cain 2007; Squires *et al.* 2011; Castillo *et al.* 2013). Similar black inclusions and microfissuring were observed within other Neat's Court bone thin sections that demonstrated macroscopic evidence for heat treatment (Deter & Barrett 2009). It was possible that these inclusions represented infiltrations of carbon that had been produced through the combustion of organic materials (Shahack-Gross *et al.* 1997; Hanson & Cain 2007; Squires *et al.* 2011; Castillo *et al.* 2013). However, these infiltrations often merged with orange features, and so it could not be determined whether they represented deposits of iron oxides or carbon.

Some of the bones from Neat's Court that demonstrated high levels of microstructural preservation retained reduced levels of collagen birefringence. Some of this reduction in birefringence had occurred as a result of the dampening effect of microstructural staining (Garland 1987; Shahack-Gross *et al.* 1997; Turner-Walker 2008). However, loss of birefringence was also apparent within unstained areas of certain bones. Loss of birefringence without an accompanying loss of histological integrity suggested that collagen had been lost by accelerated hydrolysis, which can be produced by low level heating of the bone for long durations (Collins *et al.* 1995; Smith *et al.* 2002; Abdel-Maksoud 2010). Evidence for other mechanisms that could have accelerated chemical loss of collagen within these remains was not forthcoming, although the exact conditions that promote this type of bone protein loss are still uncertain (Smith *et al.* 2002; 2007). The rarity of this form of collagen loss within the whole study sample suggested that a specific anthropogenic processes rather than an environmental factor were likely to have accelerated hydrolysis of collagen within the Neat's Court samples (Smith *et al.* 2007).

The coincidence of evidence for heat treatment and high histological integrity of the Neat's Court skeletons allowed for speculation regarding whether these features were related to the inhibition of putrefaction. One of the mechanisms of preservation forwarded to explain the mummification of the Cladh Hallan bodies was smoking of the corpse through long term exposure over a fire (Parker Pearson *et al.* 2005; Morley 2011, personal communication). Such

treatment would have desiccated the soft tissues and deprived putrefactive bacteria of the moisture required for their proliferation (Aufderheide 2003; Parker Pearson 2005; Lynnerup 2007). Desiccation would start at a superficial level and progress inwards. Therefore, if the Neat's Court bodies had been smoked, but not eviscerated, the bone would have been exposed to minor variable levels of internal putrefactive action before the bacteria were neutralised (Parker Pearson *et al.* 2007). Cadavers would have to be smoked for significant lengths of time before the soft tissues were preserved (Aufderheide 2003). Macroscopic signs of burning were concentrated on the dentition and the long bone epiphyses, areas of the anatomy that are not well-protected by soft tissue (Deter & Barrett 2009; Morley 2011, personal communication). These affected zones represented parts of the skeleton that would have been most vulnerable to the effects of heat within a fleshed body (Morley 2011, personal communication).

One of the Neat's courts samples that had been extensively bioeroded by bacteria originated from a skeleton that demonstrated macroscopic signs of heat treatment. This observation suggested that the link between heat treatment and histological preservation was false. However, the results from the Cladh Hallan assemblage as well as the Derrycashel bog body had suggested that methods of mummification that did not involve evisceration could have exposed bones to high levels of putrefactive action (Parker Pearson *et al.* 2005; 2007). High histological integrity of previously-mummified samples may represent a trend rather than an absolute. It was possible that the burned and bioeroded Neat's Court specimen had been ineffectually smoked, leading to extensive internal putrefaction and bone bioerosion.

The Neat's Court remains demonstrated high incidences of Wedl tunnelling. The Wedl tunnelling observed within these samples was more extensive and took up larger proportions of the bone microstructure than that observed within bones from other sites. The Wedl tunnelling could be seen to infiltrate the bone from the Haversian canals. Fungal tunnelling is normally observed to originate from the periosteal bone surface (Marchiafava *et al.* 1974; Hackett 1981; Jans *et al.* 2004; Nielsen-Marsh *et al.* 2007). However fungal attack was still concentrated within the internal areas of bone that had not been exploited by bacteria.

The results of the current study had suggested that Wedl tunnelling was more likely to have occurred within bones that had been kept above ground, possibly whilst retaining some soft tissue (Jans *et al.* 2004). However, it could not be determined whether the same factors had contributed to the instigation of Wedl tunnelling within every assemblage. It was likely that other unknown mechanisms encouraged fungal exploitation of the bone. The appearance of

fungal tunnelling within the Neat's Court remains might be consistent with the mummification hypothesis had preserved bodies been curated above ground for extended periods of time. However, only two of the three histologically well-preserved 'mummified' specimens demonstrated Wedl tunnelling. Three of the extensively-bioeroded specimens had been attacked by fungi. Fungal tunnelling was absent from a bone sample that was free from bacterial attack. A link between fungal tunnelling and curation might be consistent with the suggestion that remains from Neat's Court were preserved and kept above ground for a time. However, the uncertain conditions required for fungal exploitation of bone suggested that this conclusion could not be sustained solely on the evidence of Wedl attack. Wedl tunnelling was not observed within bone samples of the putatively formerly-mummified skeletons from other site assemblages.

The higher occurrences of Wedl tunnelling identified within butchered and possibly cooked domesticate bone had indicated that fungal exploitation might be facilitated by the dissolution of bone mineral encouraged by low level heating (Hedges 2002; Jans *et al.* 2004; Turner-Walker 2012). Wedl tunnelling was observed within all but one of the Neat's Court bone samples that demonstrated evidence for heat treatment, and one extra sample that did not. It was difficult to determine whether the heightened incidence of fungal tunnelling amongst the Neat's Court remains was indicative of any single taphonomic process.

Most of the bone samples from Neat's Court demonstrated high levels of orange staining inclusions and infiltrations. The appearance of these features may provide evidence that these individuals had decomposed under anoxic conditions (Hollund *et al.* 2012). However, the results of the current study suggested that iron oxide staining, infiltrations and inclusions were commonly observed within most archaeological bone thin sections (Garland 1987; Grupe & Dreses-Werringloer 1993; Schultz 1997). Similar staining and inclusions were observed within thin sections of bone from the Deverel-Rimbury cremation deposit, a nearby Roman cremation inhumation and a disarticulated cow bone that was recovered from within a few metres of the round barrow (Morley 2011, personal communication). Each of these bones had either been cremated or disarticulated and so it was unlikely that iron staining and inclusions had been produced by bodily decomposition under anoxic conditions (Hollund *et al.* 2012). The same kinds of staining, inclusions and infiltrations were also observed within the Neat' Court bone samples that had been extensively bioeroded by bacteria. These results suggested that the extensive orange microstructural staining observed within the Neat's Court samples was not a result of decomposition within an anoxic environment but interactions between the bone and iron oxides present the within burial environment (Hollund *et al.* 2012).

8.2.4.7 South Dumpton Down Round Barrow, Kent, U.K.

All of the samples from South Dumpton Down demonstrated extensive bacterial bioerosion which indicated that that they had been exposed to substantial levels of putrefaction. There was a slight discrepancy in the level of bacterial attack between the Early Bronze Age and Iron Age samples. The one Iron Age sample demonstrated a heightened Whole OHI score compared with the Bronze Age specimens. The results from the Iron Age sample were discussed alongside the other sites that dated to this period.

All of the burials that dated to the Bronze Age demonstrated Whole OHI scores of one or zero which were consistent with all individuals having been buried intact soon after death (Nielsen-Marsh & Hedges 2000; Jans *et al.* 2004; Nielsen-Marsh *et al.* 2007). This interpretation could be applied to the Bronze Age individuals recovered from the pit underneath the barrow and the remains that lay in the grave to the north of this structure (Perkins 1994). The partial disarticulation of these samples meant that it was possible that some of these remains had been primarily buried elsewhere before being placed within one of the three pits. However, the completeness of the skeletons suggested that the *in situ* environment represented their primary depositional context (Perkins 1994; Gibson 2007).

The results of the histological analysis were consistent with the original interpretations of the site, which suggested that the South Dumpton Down Bronze Age assemblage had accumulated as a result of the successive interment and manipulation of whole bodies (Perkins 1994; Gibson 2007). This scenario was supported by the stratigraphic evidence that earlier remains were more likely to demonstrate higher levels of skeletal disarticulation (Perkins 2004). Disarticulation of remains was promoted by disturbance as a result of successive interment and the selective retrieval of particular skeletal elements.

The skulls were missing from most of the Bronze Age individual from the pit, and it was likely that each successive act of interment was accompanied by the retrieval of a skull from a previous deposition (Perkins 1994). The high levels of histological attack and partial articulation observed within these remains suggested that this disturbance had taken place after the putrefaction stage, but before the bodies had skeletonised. This interpretation was supported by the radiocarbon dates from the skeletons, which were indistinguishable from one another and suggested that death and interment of each individual had occurred within a short space of time (Perkins 1994). Gibson (2007) argued that the rites practised at Early Bronze Age South Dumpton Down represented a continuation of Neolithic funerary practices

of successive interment and disturbance albeit performed within a set of pits rather than a tomb. Patterns of bacterial bone bioerosion and disarticulation at South Dumpton Down were similar to those observed amongst the Neolithic remains from Frälsegården, Whitwell Quarry and Beeston Tor.

Most of the Bronze Age remains from South Dumpton Down were free from microstructural staining. Superficial brown staining was observed within one sample. The results from the whole assemblage suggested that the occurrence of brown staining was loosely associated with humic factors released through the decomposition of organic grave goods. The presence of brown staining might suggest that the grave once contained perishable items. The stained sample had been extensively bioeroded by bacteria, which indicated that humic staining had not inhibited bacterial exploitation (Hedges 2002; Jans *et al.* 2004). Infrequent orange inclusions and infiltrations observed amongst the South Dumpton Down specimens were consistent with similar features recorded within most archaeological bones used in the current study. Their presence was probably the result of interactions between the bone and iron oxides in percolating groundwater (Garland 1987; Grupe & Dreses-Werringloer 1993; Schultz 1997). The lack or orange staining within these samples suggested that iron oxides were not prevalent within the immediate burial environment.

8.2.5 Bronze Age Summary

All but one of the Bronze Age site assemblages included articulated remains whose diagenetic signatures were consistent with immediate burial. The distribution of these sites across Britain and from different phases of the Bronze Age suggested that primary inhumation was afforded to a significant proportion of individuals in Bronze Age Britain (Jans *et al.* 2004; Nielsen-Marsh *et al.* 2007). Bone samples from articulated skeletons that demonstrated limited or low levels of bacterial bioerosion were exclusive to Bronze Age site assemblages. This trend was partly responsible for the phase-specific variation in the presence of bacterial bioerosion amongst the Later Prehistoric samples. Bronze Age articulated and disarticulated samples were more likely to have remained free from bacterial bioerosion than remains from any other phase. These patterns of bacterial attack were largely responsible for the peak in the Later Prehistoric distribution of Whole OHI scores at five, particularly within the articulated assemblage. These Bronze Age sites included Cladh Hallan, where there was taphonomic evidence that the articulated skeletons which demonstrated these diagenetic signatures had previously been

mummified (Parker Pearson *et al.* 2005; 2007). The analysis of the Historical assemblage had established the rarity of this diagenetic signature within the bones of buried individuals. The suggestion that this signature of putrefactive bone bioerosion was consistent with mummification had been confirmed to some extent by histomorphological studies of mummified bone by the present and previous studies (Weinstein *et al.* 1981; Thompson & Cowen 1984; Stout 1986; Brothwell & Bourke 1995; Hess *et al.* 1998; Parker Pearson *et al.* 2005).

The low numbers of samples that were obtained from certain Bronze Age sites meant that the interpretation of diagenetic signatures as evidence for mummification was tenuous on a site-by-site basis and could be dismissed as the result of limited sampling having captured a skewed distribution of natural variation. However, the persistent occurrence of histologically well-preserved articulated skeletons at numerous Bronze Age sites, especially when contrasted to the lack of similar remains from Iron Age, Neolithic and Historical contexts, supported the assertion that they represented an unusual form of treatment that was specific to the Bronze Age. The only form of treatment that consistently produces articulated skeletons that have experienced no or little putrefactive bioerosion is mummification (Weinstein *et al.* 1981; Thompson & Cowen 1984; Stout 1986; Brothwell & Bourke 1995; Hess *et al.* 1998; Parker Pearson *et al.* 2005).

The Bronze Age exclusivity of diagenetic signatures of mummification bolstered site-specific inferences of these rites and increased the likelihood that similar treatment was responsible for the atypically high levels of histological preservation within Bronze Age articulated samples of bone that had been recovered from anoxic environments. Phase had a larger influential effect on the presence of bacterial bioerosion than environmental anoxia. It was more likely that the absence of bacterial bioerosion from the anoxic-deposited Bronze Age samples was a result of treatment than anoxic environment, although the potential effect of environmental anoxia could not be disregarded entirely.

Histological preservation within the Bronze Age disarticulated samples was also higher than within similar remains from Iron Age and Neolithic contexts. The only post-neonatal Neolithic disarticulated remains that demonstrated similar levels of histological preservation had been taken from the bones of dismembered individuals that were unlikely to have experienced bodily putrefaction. Sub-aerial exposure would have limited the levels of putrefaction a bone experienced, however many of the Bronze Age disarticulated samples were free from putrefactive bacterial attack (Bell *et al.* 1996; Fernández-Jalvo *et al.* 2010; Simmons *et al.*

2010). This diagenetic signature was more consistent with prior mummification (Weinstein *et al.* 1981; Thompson & Cowen 1984; Stout 1986; Brothwell & Bourke 1995; Hess *et al.* 1998; Parker Pearson *et al.* 2005).

The ostensibly articulated formerly mummified remains from Cladh Hallan had been constructed out of the disarticulated parts of several individuals (Parker Pearson *et al.* 2005; 2007; Hanna *et al.* 2012). When considered alongside the results from the articulated Bronze Age samples, it was more parsimonious to consider the histologically well-preserved disarticulated Bronze Age remains as products of prior mummification that had not retained their articulation. The familiar image of mummified remains is one of articulated fleshed bodies, but high proportions of mummified specimens are recovered in variable stages of articulation and decomposition (Aufderheide 2003; Lynnerup 2007). Histological signatures of mummification were identified in bones within sites ranging from the Outer Hebrides of Scotland to the northern coast of Kent and from contexts attributable to the Early, Middle and Late phases of the Bronze Age. These results indicated that mummification may have been practised on a widespread scale in Britain throughout the Bronze Age.

The variability of putrefactive bacterial bioerosion observed amongst the potentially mummified remains as well as their diverse levels of articulation indicated that any methods of preservation were only sporadically successful in each case. There was evidence that the Cladh Hallan remains were mummified by temporary submersion within a sphagnum peat bog (Parker Pearson *et al.* 2005). The inconsistencies involved with mummification in a bog environment were consistent with the variable levels of anatomical articulation amongst the Cladh Hallan skeletons (Turner 1995; Aufderheide 2003). The immaculate levels of histological preservation within the bone samples from Cnip and Ingleby Barwick indicated that visceral bacteria were separated from the bone in the early *post mortem* period and suggested that evisceration may have been involved in any preservative process (Aufderheide 2003; Jans *et al.* 2004; Nielsen-Marsh *et al.* 2007). The evidence that the Neat's Court remains were exposed to low level heat treatment suggested that these bodies may have been preserved through smoking (Morley 2011, personal communication). These observations were consistent with the conclusions of Parker Pearson *et al.* (2005: 543) that methods of mummification practised in the Bronze Age were likely to have made innovative use of natural resources. The construction of composite bodies out of the mummified remains of multiple individuals at Cladh Hallan was interpreted as a symbolic attempt to unite the ancestors of several lineages (Parker Pearson 2005; 2007). The variable patterns of disarticulation and putrefactive bone bioerosion within the bone samples of the potential Bronze Age mummies suggested that such reconstructions

may have represented practical attempts to account for inconsistencies in maintaining an individual's form associated with inefficient preservative methods (Aufderheide 2003).

Radiocarbon dates from the potentially mummified Bronze Age remains from Ingleby Barwick, Cnip Headland and Cladh Hallan were all earlier than conventional burials from the same sites (Annis *et al.* 1997; Parker Pearson *et al.* 2005; Lelong 2011). One of the radiocarbon dates from the Langwell Farm Cist skeleton was anomalously early (Lelong 2012). The dating evidence from Cladh Hallan established that mummified bodies may have been curated for decades or centuries before they were buried (Parker Pearson *et al.* 2005). The early dates of some of the putative former-mummies identified by the current study might suggest that there was a similar delay between the death and burial of these individuals. The formerly--mummified remains from Cnip, Neat's Court and Ingleby Barwick were all recovered alongside skeletons that demonstrated diagenetic signatures consistent with inhumation soon after death. It was possible that interment of mummified and untreated bodies had occurred simultaneously at some sites (Annis *et al.* 1997; Lelong 2011; Morley 2011, personal communication).

8.2.6 Iron Age

8.2.6.1 Bilham Farm Enclosure, South Yorkshire, U.K.

The bone samples taken from the two articulated individuals excavated from Bilham Farm demonstrated extensive levels of bacterial bioerosion that suggested the bones had been exposed to high levels of putrefaction. This result was consistent with both bodies having been buried intact soon after death (Rodriguez & Bass 1983; 1985; Bell *et al.* 1996; Nielsen-Marsh & Hedges 2000; Jans *et al.* 2004; Nielsen-Marsh *et al.* 2007). The microstructure of these samples had not been stained, which suggested that the burial sediment had not contained large quantities of iron oxides. The orange inclusions found within both specimens were similar to those observed within the majority of other bones from the whole study sample, and most likely represented deposits of iron oxides transported by percolating groundwater (Garland 1987; Grupe & Dreses-Werringloer 1993; Schultz 1997).

Small quantities of Wedl tunnelling were observed within small islands of bone within both samples that had been spared by bacteria. The small sample size meant that it was difficult to gauge the significance of the Wedl tunnelling, as it was possible that sampling had captured an unrepresentative cohort. The overall results of the present study, as well as other research

into bioerosion, had suggested that Wedl tunnelling is more likely to appear within bones that had decomposed on the ground surface whilst retaining small amounts of soft tissue (Marchiafava *et al.* 1974; Jans *et al.* 2004). The presence of Wedl tunnelling within the Bilham remains may be significant when it is considered that the state of articulation of the adult individual suggested that this grave had been reopened in order to manipulate the body whilst it was decomposing (Merrony 2012, personal communication). The reopening of the grave may have provided saprophytic fungal species sufficient opportunity to exploit the remaining bone proteins and soft tissues before the body was reburied (Jans *et al.* 2004). This manipulation must have taken place during the later stages of decomposition, after the bone had been mostly bioeroded by putrefactive bacteria. There was no evidence that the grave of the sub-adult individual had been re-opened, even though the bones of this individual had also been affected by Wedl tunnelling (Merrony 2012, personal communication). It was possible that the grave could have been reopened in a way that had not disturbed the anatomical articulation of the skeleton.

8.2.6.2 Danebury & Suddern Farm, Hampshire, U.K.

All but one of the bones sampled from the Danebury and Suddern Farm assemblages demonstrated moderate to severe levels of bacterial bioerosion. The exceptional sample had been subjected to minor levels of bacterial attack. These results suggested that majority of individuals had been treated in ways which exposed the bones to variable extensive levels of putrefactive attack. The distribution of Whole OHI scores across this population varied from the Historical baseline model. These results suggested that most of the remains from these sites had decomposed within something akin to a burial environment, but that prior or subsequent treatment had variably limited bone exposure to putrefaction (Nielsen-Marsh & Hedges 2000; Jans *et al.* 2004; Nielsen-Marsh *et al.* 2007).

Putrefaction of the Danebury and Suddern Farm remains may have been variably altered had the burial sediments been subject to frequent episodes of anoxia through waterlogging (Turner-Walker & Jans 2008; Hollund *et al.* 2012). There was no evidence that any of the burial sediments had been regularly waterlogged (Cunliffe 1983; 1984; Cunliffe & Poole 2000). Bacterial bioerosion within the Danebury & Suddern Farm samples was much more extensive than that observed within the waterlogged Historical remains. It was improbable that environmental factors were responsible for the patterns of bacterial attack observed within

the Danebury & Suddern Farm sample. Variations in bacterial bioerosion within this assemblage must have been related to the nature of their early *post mortem* treatment (Jans *et al.* 2004; Nielsen-Marsh *et al.* 2007).

Identification of cortical weathering on bone from other Iron Age sites that yielded skeletal assemblages similar to those from Danebury, such as Gussage-all-Saints and Maiden Castle, had suggested that bodies had been excarnated through sub-aerial exposure (Redfern 2008). The extensive bacterial bioerosion observed within the Danebury & Suddern Farm samples was not consistent with sub-aerial exposure, as this rite would have exposed the bones to only limited soft tissue putrefaction (Rodriguez & Bass 1983; 1985; Bell *et al.* 1996; Fernández-Jalvo *et al.* 2010; Simmons *et al.* 2010). The effect of seasonality on the abundance of skeletonising insect may have produced variation in the level of putrefaction that a bone experienced (Rodriguez & Bass 1983; 1985; Wilson *et al.* 2007; Simmons *et al.* 2010; Meyer *et al.* 2013). However, soft tissue loss via insect activity would be expected to have limited bone exposure to soft tissue putrefaction to a greater extent than what was apparent within the Danebury & Suddern Farm samples (Bell *et al.* 1996; Turner-Walker *et al.* 2008; Fernández-Jalvo *et al.* 2010; Hollund *et al.* 2012). An investigation into the weathering patterns amongst the Danebury remains had concluded that they were unlikely to have been sub-aerially exposed (Madgwick 2008). Only low numbers of bones from the Danebury site demonstrated carnivore gnawing or weathering that characterises sub-aerially exposed bone (Madgwick 2008; Redfern 2008).

The slightly elevated distribution of Whole OHI scores within the bones from Danebury & Suddern Farm sites resembled what was observed within both Neolithic cave deposits and the remains bones from the Royal Mint Black Death cemetery. Slow, extensive putrefaction within the cave-deposited remains had most likely been regulated by soft tissue loss via restricted insect activity (Terrell-Nield & MacDonald 1997). The articulation of the skeletal remains from the Black Death Royal Mint cemetery suggested that the variability in patterns of bacterial bone bioerosion was related to a delay between death and burial (Grainger *et al.* 2008). Consideration of these examples combined with the contextual information suggested that the distribution of bacterial bioerosion within the Danebury & Suddern Farm samples was explained either by bodies having been left to decompose above ground for a short while before being buried, or by deposition of the dead within an environment that variably restricted insect access.

The skeletal articulation of the Danebury and Suddern Farm assemblages was highly variable, ranging from articulated whole skeletons to discrete disarticulated elements (Cunliffe 1983;

1984; Cunliffe & Poole 2000). When the assemblage was separated into articulated, partially articulated and disarticulated remains, the distribution of Whole OHI scores amongst the first two categories was similarly variable and elevated, but histological preservation within the disarticulated bones was uniformly low. This result suggested that the disarticulated remains had been treated consistently in a way that ensured they were exposed to the highest levels of putrefactive bioerosion. The best explanation for this observation was that individuals represented by disarticulated bone had been buried soon after death and that their bones had been disinterred and redeposited after decomposition had run its full course (Bell *et al.* 1996; Nielsen-Marsh & Hedges 2000; Jans *et al.* 2004; Nielsen-Marsh *et al.* 2007). The disarticulated material was distributed sporadically around numerous contexts, usually pits, within the Danebury site. It was possible that the disarticulated bones represented 'charnel' material; bones that had been disinterred from fully-decomposed primary burials as a result of later activity. The arrangement of Danebury changed considerably over the course of its use, and it was possible that the pits which held human remains had been encountered during the production of new features (Cunliffe 1983; 1984).

The suggestion that the individuals represented by the disarticulated remains had been buried soon after death clashed with the evidence for carnivore gnawing and fresh bone fractures within the disarticulated assemblage as a whole and from two of the disarticulated elements that had been sampled (Cunliffe 1983; 1984). These types of alterations would only be expected to occur within unburied fresh bone (Cunliffe 1984). Some articulated and partially-articulated specimens demonstrated equally high levels of bacterial bioerosion, and it was possible that all remains from Danebury & Suddern Farm had been treated similarly. The high levels of bacterial bioerosion amongst the disarticulated remains may have represented a skewed representation of the overall distribution.

All of the human remains from Danebury had been recovered from storage pits rather than purpose-cut graves (Cunliffe 1983; 1984). These pits were sometimes found to have been half-filled with domestic refuse before the body was interred (Cunliffe 1983; 1984). The build-up of silts around certain skeletons suggested that a proportion bodies had originally lain within open pits for a duration before they were buried. Accumulations of silts were also observed within the quarry graves at Suddern Farm (Cunliffe & Poole 2000). A scenario where bodies were exposed in pits for limited lengths of time provided a plausible explanation for the levels of putrefactive bone bioerosion. Bodies exposed in pits would have been subjected to rapid soft tissue loss via skeletonising insects (Simmons *et al.* 2010). If the remains were buried before the majority of the soft tissue was lost, the bones would still have been subject to

substantial but limited levels of soft tissue putrefaction. The similarity in the levels of bacterial bioerosion amongst the articulated and partially articulated remains suggested they represented different parts of the same process. Partially-articulated anatomical parts as well as disarticulated bones may have been removed from whole bodies that had been allowed to decompose within an open pit. This interpretation suggested that pits containing bodies may have been left open so that distinct anatomical parts could be retrieved after the remains had decomposed far enough to facilitate their removal. Burial of the remains before skeletonisation would ensure that the bones were exposed to only minimal weathering. The samples that demonstrated the highest levels of bacterial bioerosion must only have been exposed for a short while before being buried.

The weakness of this interpretation was that it would be expected that if bacterial bone bioerosion was related to duration of exposure within a pit, levels of disarticulation would correlate within bacterial attack. The entirely disarticulated bones must have been removed after the body had mostly composed within the open pit. These remains would have experienced only limited levels of soft tissue putrefaction and should have demonstrated the highest levels of histological preservation, yet the opposite scenario was observed. This prediction assumed that the disarticulated remains were originally removed as single elements, rather than as parts of an anatomical section that subsequently disintegrated.

Articulated remains must have been buried soon after deposition, before soft tissue had been lost, and should have demonstrated the highest levels of putrefactive bioerosion. Whole OHI scores amongst the articulated remains were variable and elevated. Partially articulated remains would have represented anatomical parts that were removed after some soft tissue loss and should have demonstrated lower levels of bacterial bioerosion than the articulated samples. Distributions of bacterial bioerosion within the partially articulated samples was similar to those observed within the articulated cohort. It was possible that seasonal variations in the rapidity of soft tissue loss within pit-interments had increased variability in putrefactive bacterial bioerosion, but the expected patterning should have been preserved to some extent (Rodriguez & Bass 1983; 1985; Wilson *et al.* 2007; Simmons *et al.* 2010; Meyer *et al.* 2013).

An alternative scenario that would account for the lack of correlation between putrefactive bone bioerosion and skeletal articulation could be that the pits were prepared in way that protected the bodies from the effects of skeletonising insects. Madgwick (2008) had suggested that the lack of cortical erosion amongst the human bone assemblage from Danebury, in spite of the evidence that remains had lain within open pits, suggested that the human skeletons

had been afforded some form of protection from modification (Madgwick 2008: 71). Patterns of bacterial bioerosion and cortical weathering could be explained had the pits been covered with textiles, leathers or plugged with another material whilst the bodies decomposed. Such coverings would have restricted, but not entirely prevented insect access, allowing the bones to experience variable extensive soft tissue putrefaction (Galloway *et al.* 1989; Goff 1991; Terrell-Nield & MacDonald 1997; Anderson 2011; Vass *et al.* 2011). Discrete skeletal elements or anatomical parts would not have become available for removal until a later decompositional stage, which would explain similarities in patterns of bacterial bioerosion within remains that demonstrated variable levels of articulation. The extent of bacterial bioerosion would not have been controlled by the length of time the body was exposed within an open pit, but the efficacy of the coverings in preventing entomological access (Bell *et al.* 1996; Terrell-Nield & MacDonald 1997; Jans *et al.* 2004; Simmons *et al.* 2010).

It was tempting to view the exposure of human remains within covered or open pits as an attempt to ensure controlled decomposition whilst allowing access to certain anatomical parts as and when they become available for use in further rituals. However, the varied levels of bacterial bioerosion observed within the articulated remains suggested that these bodies had decomposed within open or covered pits before being buried without any removal of anatomical elements. This finding suggested that the rites practised at Danebury were not solely concerned with obtaining relics, or that the characteristics associated with the individual or the nature of their decomposition disqualified the use of their bones in further depositional processes.

The Suddern Farm burials had originated from single graves within a discrete cemetery located on the outside of a settlement (Cunliffe & Poole 2000). Cunliffe & Poole (2000: 168) suggested that it was likely these burials represented a different funerary tradition from that which was practised at the Danebury hillfort. It was possible that the type of treatment observed at Suddern Farm constituted the rite afforded to the majority of individuals during the British Iron Age (Cunliffe & Poole 2000: 168). Most of the skeletons from the Suddern Farm cemetery showed some level of disarticulation that suggested that bodies had been manipulated after they had partially decomposed (Cunliffe & Poole 2000). Cunliffe & Poole (2000: 168) believed that this disturbance was the result of new grave digging. However, the evidence for the persistent removal of particular skeletal elements hinted that primary burial did not represent the terminal form of treatment (Cunliffe & Poole 2000).

The two individuals that were sampled for this project (C19 & C20) from Suddern Farm had been interred within the same pit and demonstrated variable levels of skeletal articulation (Cunliffe & Poole 2000). The skulls had been removed from both skeletons. The original interpretation of this context was that one body had been originally buried within the grave and was subsequently disturbed by the insertion of the second individual (Cunliffe & Poole 2000: 168). This scenario implied that the grave was reopened a second time to remove the skull of the secondary deposit. The level of bacterial bioerosion observed within the bones of these remains was consistent with those from the Danebury articulated and partially articulated samples. The elevated Whole OHI scores of the Suddern Farm samples placed them towards the higher end of the Danebury distribution, farther away for the Historical baseline signature. The similarity between the distribution of bacterial bioerosion and skeletal articulation amongst the Danebury and Suddern Farm remains suggested that, contrary to the conclusions of Cunliffe & Poole (2000: 168), both assemblages had been produced by similar processes. It was likely that the Suddern Farm individuals sampled for the current project and, by extension, the majority of similarly-treated remains from the cemetery, had been allowed to decompose within covered or open pits before they were buried. Partial disarticulation of remains would have occurred during the pre-burial retrieval of skeletal elements such as skulls. The presence of complete skeletons within the Suddern Farm cemetery further suggested that retrieval of relics was not the sole purpose of this treatment and that burial did not always follow the acquisition of anatomical parts.

The Danebury & Suddern Farm assemblages demonstrated slightly higher incidences of Wedl tunnelling than what was found typically amongst most assemblages included in the present study. Wedl tunnelling was more common amongst the partially articulated specimens at Danebury & Suddern Farm, although fungal attack was also found within the bones of one articulated individual. The results from the Primary Analysis suggested that fungal tunnelling appeared within bone samples that were likely to have been exposed above ground for a length of time, possibly whilst still retaining some soft tissue (Jans *et al.* 2004). Higher occurrences of Wedl tunnelling within the Danebury and Suddern Farm samples was consistent with skeletonised or partially skeletonised bodies having lain in an open environment.

The Danebury samples did not consistently demonstrate a preserved periosteal cortex. The destruction of this part of the bone microstructure is not enabled by internal bacterial attack, but must occur as a result of exogenous erosion. Bones from all contexts within Danebury & Suddern Farm had lost their periosteal surface. The results from the Primary Analysis had

suggested that silt burial environments may have promoted periosteal loss. However, some weathering of the periosteal bone surface would also be consistent with prior exposure of the remains in an open or covered pit (Madgwick 2008). Bones that had lost their periosteal surfaces included discrete disarticulated samples whose patterns of bacterial bioerosion suggested that they had been disarticulated via primary burial. However, periosteal loss was higher within bone samples from articulated and disarticulated bones. This result supported the assertion that the articulated and partially-articulated bones were treated differently to the disarticulated assemblage. Greater loss of the periosteal surface from articulated and partially articulated remains was consistent with the interpretation that these remains had more often been left to decompose within open pits and were exposed to greater levels of weathering, whereas the disarticulated samples originated from bodies that had decomposed whilst buried and had been protected from cortical erosion.

The anomalous sample from Danebury that demonstrated limited levels of bacterial bioerosion was recovered as a discrete disarticulated skeletal element (Cunliffe 1984). The cortex of this specimen had been heavily weathered, burnt and gnawed by a carnivore (Cunliffe 1984). The entire bone microstructure was discoloured yellow. The character of the discolouration was not consistent with infiltration by extraneous elements, but resembled the colour changes associated with low-level heat treatment (Shahack-Gross *et al.* 1997; Hanson & Cain 2007; Squires *et al.* 2011). Most of the bone microstructure was perfectly preserved, but collagen birefringence within the histologically-intact areas was low. This observation suggested that collagen had been removed via accelerated collagen hydrolysis, which was consistent with this specimen having been exposed to low level burning (Hackett 1981; Smith *et al.* 2002; Smith *et al.* 2007; Abdel-Maksoud 2010).

The limited signature of bacterial bioerosion observed within the anomalous sample, Deposit 130, was consistent with it having originated from a body that decomposed on the ground surface (Bell *et al.* 1996; Jans *et al.* 2004; Turner-Walker & Jans 2008; Fernández-Jalvo *et al.* 2010; Hollund *et al.* 2012). Burning of the whole corpse would have interfered with the proliferation of visceral bacteria (Polson *et al.* 1985). The link between putrefaction and bacterial bioerosion indicated that the bacterial attack must have occurred before the bone was exposed to heat (Bell *et al.* 1996; Jans *et al.* 2004; Nielsen-Marsh *et al.* 2007; Smith *et al.* 2007). This putative treatment contrasted with the processes that had been afforded to individuals that constituted the rest of the assemblage. It was possible that the Deposit 130 had been subjected to similar processes as the other remains from Danebury & Suddern Farm and represented either an outlier to the distribution of bacterial bioerosion, or had originated

from an individual that had not been covered or buried effectively prior to skeletonisation. However, the evidence for additional exposure to low level heating supported the suggestion that these remains had been afforded a deviant form of funerary treatment.

The Danebury remains were mostly free from the orange inclusions and staining that were present within the majority of archaeological remains were used in the current study (Garland 1987; Grupe & Dreses-Werringloer 1993; Schultz 1997). The lack of these features were probably the result of the burial environment including a low abundance of iron oxides. This observation was consistent with the burial contexts of the Danebury skeletons, which consisted of eroded chalk silt and domestic rubbish. Many of the Danebury bones demonstrated grey inclusions. The results of the overall analysis had suggested that these features were reflective of the burial environment. The inclusions observed in the Danebury and Suddern Farm samples probably consisted of particles of chalk that had made their way inside the bone porosities (Garland 1987; Grupe & Dreses-Werringloer 1993; Schultz 1997).

8.2.6.3 Hornish Point Settlement, South Uist, U.K.

The bones of the Hornish Point Boy specimen had been extensively bioeroded but maintained a preserved periosteal fringe. Barber *et al.* (1989: 778) had suggested that partial decomposition and special treatment of this individual indicated that the body may have been lost at sea initially. An aquatic environment would have interfered with putrefaction and bone bioerosion (Cotton *et al.* 1987; Rodriguez 1997; Pakosh & Rogers 2009; Heaton *et al.* 2010; Maria & Docents 2010). Archaeological and forensic bones recovered from aquatic environments tend to remain free from bacterial bioerosion (Ascenzi & Silvestrini 1984; Bell & Elkerton 2008; Turner-Walker & Jans 2008). The evidence that the Hornish Point Boy bones had been exposed to high levels of putrefactive bioerosion suggested that the body had not spent the early *post mortem* period within an aquatic context.

The osteolytic microorganisms that erode bone microstructure in aquatic contexts produce Wedl tunnelling (Ascenzi & Silvestrini 1984; Bell & Elkerton 2008; Turner-Walker & Jans 2008). No Wedl tunnelling was observed within the Hornish Point specimen. Initial evidence of marine-type bioerosion could have been obliterated by the subsequent bacterial colonisation. However, Wedl tunnelling micro-organisms are thought to be exogenous and are most often observed to bore through the periosteal cortex before travelling inwards towards the mid-section (Hackett 1981; Jans *et al.* 2004; Bell & Elkerton 2008; Turner-Walker & Jans 2008).

Wedl MFD should still have been visible within the preserved periosteal band of the Hornish Point specimen had the skeleton been attacked by marine microorganisms. Whilst the absence of marine-type bioerosion could not be used to rule out the possibility that the Hornish Point Boy had been lost at sea, the overriding presence of a common terrestrial pattern of bioerosion indicated that these remains had decomposed on land.

The extensive patterns of putrefactive bioerosion observed in the samples from the Hornish Point individual was consistent with immediate intact burial (Rodriguez & Bass 1983; 1985; Bell *et al.* 1996; Nielsen-Marsh & Hedges 2000; Jans *et al.* 2004; Nielsen-Marsh *et al.* 2007; Jans 2008). The partial disarticulation of the Hornish Point skeleton was likely to have occurred as a result of primary burial. Partial articulation of anatomical elements within this individual suggested that it had been disinterred after putrefactive bone bioerosion had completed but before the body had skeletonised.

The distribution of the skeleton amongst the pits broadly corresponded to the site where the vertebrae had been severed (Barber *et al.* 1989). This observation suggested that the act of severance was committed in order to fit the partially-decomposed remains within the four pits, rather than as a *peri mortem* act of ritual slaughter (Barber *et al.* 1989). This finding indicated that the mutilation of the body had taken place after its initial decomposition, as the act of severance alone would not have allowed the remains of a fresh corpse to have been distributed across the four pits. There was no obvious reason why the body could not have been entirely dismembered to fit amongst the pits if this act had been carried out immediately after death (Barber *et al.* 1989). The histological evidence was consistent with the Hornish Point remains having been buried before they were mutilated. Severance of the body would have interfered with transmigration of putrefactive bacteria, either through the separation of the viscera from the bones or exsanguination, and would have limited bacterial bone bioerosion (Jans *et al.* 2004).

The vertebrae are held with strong ligaments and are usually amongst the last skeletal elements to disarticulate (Micozzi 1986; Roksandic 2002). Decomposition of a buried body is variable and any rate of skeletonisation presumed by the buriers of the Hornish Point individual was likely to have been inaccurate. It was possible that the Hornish Point Boy was initially buried in order to disarticulate the remains so that they could have been placed amongst the four pits. However, decomposition of the body may not have been as advanced as expected when it was eventually uncovered. Rather than having to rebury the remains, it may have been deemed practical or appropriate to sever the half-decomposed body to allow it

to be distributed across the four pits. The Hornish Point specimen demonstrated superficial levels of orange staining and inclusions. The results of the present study as well as previous projects suggested that these features were very common and occurred as a result of interactions between the bone and iron oxides located in the burial environment and percolating groundwater (Garland 1987; Grupe & Dreses-Werringloer 1993; Schultz 1997; Hollund *et al.* 2012).

8.2.6.4 South Dumpton Down Enclosure, Kent, U.K.

The slightly elevated Whole OHI score of the Iron Age skeleton from South Dumpton Down could have occurred as a result of natural variation in bacterial bioerosion within buried remains (Jans *et al.* 2004). This level of histological preservation was represented quite frequently amongst the Historical Baseline distribution. However, the OHI score of the South Dumpton Down Iron Age specimen also matched the modal value observed amongst the Danebury and Suddern Farm Iron Age assemblages. The Iron Age skeleton from South Dumpton Down was retrieved from a pit that had silted up naturally before it was filled by domestic refuse (Perkins 1994). The similarities between this specimen and the Danebury & Suddern Farm burials circumstantially suggested that the South Dumpton Down individual had decomposed within an open or covered pit before it was buried. Restriction of putrefactive bone bioerosion would have been caused by the intermittent access granted to skeletonising invertebrates by the depositional context.

The South Dumpton Down Iron Age specimen was complete and in articulation when it was recovered and represented another example of an Iron Age body whose exposure within a pit had not been enacted to facilitate the retrieval of body parts during decomposition. No Wedl tunnelling was observed within the South Dumpton Down sample. However, Wedl tunnelling was not present within all bones recovered from Danebury and Suddern Farm. The Iron Age specimen from South Dumpton Down demonstrated no microstructural staining. Orange inclusions of the kind that were found in abundance amongst the majority of remains sampled for this study occurred infrequently within this sample. It was likely that these inclusions had formed through the precipitation of iron oxides out of percolating groundwater (Garland 1987; Grupe & Dreses-Werringloer 1993; Schultz 1997).

8.2.7 Iron Age Summary

Most Iron Age individuals appeared to have been treated to some form of burial combined with prior and/or subsequent exposure and manipulation (Cunliffe 1983; 1984; Barber *et al.* 1989; Perkins 1994). The Iron Age remains were obtained from opposite ends of Britain, but interpretations of treatment were quite consistent. Despite variation in levels of skeletal articulation across different sites, these results suggested that all remains represented different stages of similar processes. The patterns of bacterial bioerosion observed amongst the bone samples from Hornish Point and Bilham Farm suggested that these remains had been buried before they were manipulated. However, the diagenetic signatures of these remains were also consistent with initial deposition in a covered pit.

There was a possible dichotomy between those remains that had been buried immediately and disinterred after decomposition had mostly completed and those bodies that had lain within an open or covered grave or pit for a certain length of time before being manipulated and buried. The disinterment and redeposition of remains associated with these processes indicated that part of their purpose was to obtain disarticulated or partially articulated skeletal elements that could be used in further activities.

The increased accessibility of the remains facilitated by exposure within a pit would have allowed for decomposition to have been monitored. Disarticulated elements could have been obtained as soon as they became available. Retrieval of anatomical parts using this method would have produced more certain results than disinterment of immediately-buried remains where the rate of decomposition would have varied. Variability in the speed of soft tissue loss within buried remains indicated that this process would not always have produced the required levels of disarticulation. Such an outcome may have been responsible for the decision to sever the vertebral column of the Hornish Point individual.

Anthropogenic dismemberment of a corpse would have provided the quickest and most practical method of obtaining disarticulated parts of an individual. Sub-aerial exposure of the dead would have ensured swift disarticulation of the remains and rapid access to bones that could be reused in further rituals (Rodriguez & Bass 1983; 1985; Mann *et al.* 1990; Campobasso *et al.* 2001; Simmons *et al.* 2010; Vass 2011). The lack of evidence for this kind of treatment suggested that Iron Age populations considered it important that individuals experienced prolonged spontaneous natural decomposition in a way that limited interference by invertebrates. It was possible that interment of bodies within open or covered pits provided

opportunities for the retrieval of relics, whilst ensuring that bodies underwent expected modes of decomposition.

The evidence that articulated skeletons had also decomposed within covered pits before they were buried suggested that the retrieval of relics was not the sole motivation behind these practices (Cunliffe 1983; 1984; Cunliffe & Poole 2000). The Bilham Farm individual had been manipulated in a way that did not involve the removal of anatomical parts (Merrony 2011, personal communication). Deposition of remains within these contexts would have allowed for the observation of prolonged processes of spontaneous bodily decomposition. The practice of a treatment that allowed the observation of decomposition, but did not always require interference with the remains, suggested that the observations themselves may have been of some utility. Patterns of bodily decomposition perhaps dictated whether or not the remains of that individual were subsequently used in further rituals. This scenario is conjectural but provides a novel perspective on the variation in decomposition and manipulation observed at Iron Age sites.

The emphasis on natural spontaneous decomposition within the Iron Age remains increased the significance of the inferred sub-aerial exposure and burning of the single individual from Danebury. The individual represented by this bone had been subjected to processes that Iron Age populations had apparently tried to prevent within most of human remains. The rapid and invertebrate-led soft tissue loss associated with sub-aerial exposure would have represented an inversion of the type of decomposition that was encouraged within most of the Iron Age remains. Purposeful exposure and burning of this individual may have represented a deviant form of funerary treatment that was deemed necessary due to aspects of that individual's identity or death. The signature of bacterial bone bioerosion within the anomalous sample was consistent with that of an individual that had died and decomposed away from the settlement and was not provided with the normal form of funerary treatment. Evidence for carnivore alteration of this bone might support this interpretation, although this kind of modification was found on other disarticulated bones sampled from Danebury. The subsequent burning of the remains may have represented a form of cleansing treatment afforded to the individuals that had died and decomposed under inauspicious circumstances.

9 CONCLUSIONS

The research questions that this project set out to answer were as follows:

1. Is there a relationship between funerary treatment and bone diagenesis that is strong enough to be detected by microscopic analysis of archaeological bone?
2. Does the relationship between bone diagenesis and funerary treatment conform to predictive models of diagenesis inferred by studies of cadaveric decomposition?
3. Is the strength and nature of the relationship between bone diagenesis and funerary rite such that certain treatments can be said to produce characteristic patterns of diagenesis that could be recognised through the microscopic analysis of archaeological bone microstructure?
4. How can measures of bone diagenesis, particularly the microscopic assessment of archaeological bones, be usefully employed in reconstructions of funerary processes?

Each of these questions could be asked of every form of bone diagenesis; bacterial bioerosion, fungal bioerosion, persistence of the periosteal surface and visual diagenetic change. Conclusions regarding relationships between each of these features and funerary processes will be discussed in turn. The purported association between bacterial bone bioerosion and funerary treatment was related to the interactions between bone and putrefaction bacteria (Child 1995a; 1995b; Bell *et al.* 1996; Jans *et al.* 2004; Nielsen-Marsh *et al.* 2007). Studies of cadaveric decomposition facilitated predictive hypotheses regarding expected patterns of bacterial bioerosion amongst the Historical and Later Prehistoric assemblages (Rodriguez & Bass 1983; 1985; Mant 1987; Galloway *et al.* 1989; Bass 1997; Manhein 1997; Rodriguez 1997; Campobasso *et al.* 2001; Vass 2011; Zhou & Bayard 2011). Assessment of the research aims within measures of bacterial bioerosion was performed through tests of these predictions. The factors that influenced other measures of diagenetic change to bone were uncertain. Questions regarding the use of these measures of bone diagenesis in inferring funerary treatment had to be assessed through the identification of the factors that most influenced their occurrence and severity.

9.1 BACTERIAL BONE BIOEROSION

The research questions set out above were assessed with regards to bacterial bioerosion using the following three hypotheses:

> **Hypothesis 1:** If bacterial bone bioerosion is linked to funerary processes, bones recovered from Historical cemeteries will demonstrate consistent patterns of internal bacterial bioerosion.

> **Hypothesis 2:** If the nature of bacterial bone bioerosion is controlled by the extent to which early funerary processes dictate bodily putrefaction, all bones from Historical cemeteries will be characterised by high levels of internal bacterial decay.

> **Hypothesis 3:** If bacterial bone bioerosion can be used to distinguish between funerary rites, there will be a significant difference between the histological signatures of bone from the Later Prehistoric and Historical periods.

Bacterial bioerosion was observed within most of the archaeological samples used in the current study and it had usually consumed the majority of the internal bone microstructure. A small number of samples (3%) had been taken from non-femoral long bones. There was no variation in bacterial bioerosion between different skeletal elements within the primary or supplementary assemblages. This result provided some tentative evidence that bacterial bioerosion does not vary amongst long bones and that variation in bacterial bioerosion with skeletal element is likely to relate to intrinsic ratios of cortical and trabecular bone.

The extent of bacterial bone bioerosion was primarily controlled by age-at-death, specifically whether the sample had been taken from a neonate. Almost 50% of neonatal bones were free from microbial bioerosion. The neonatal/post-neonatal dichotomy primarily dictated whether or not a bone was likely to have been bioeroded by bacteria. This patterning could only be explained by the sterility of the human intestinal tract at birth (Mackie 1999; White 2010). The neonatal remains that were free from bacterial bioerosion were likely to represent those individuals that were stillborn or had died before they had developed the gut microbiota

responsible for non-Wedl MFD (White 2010). Histological preservation of neonatal remains was not a reliable indicator of putrefaction relating to early *post mortem* treatment.

Most bones that had been recovered from waterlogged anoxic environments had been bioeroded by bacteria, but as a whole they demonstrated higher levels of histological preservation than remains from aerobic contexts. This result was expected, given that waterlogged environments are known to interfere with soft tissue decomposition and putrefactive bioerosion (Polson *et al.* 1985; Mant 1987; Mann *et al.* 1990; Janaway 1996; Rodriguez 1997; Nielsen-Marsh & Hedges 2000; Campobasso *et al.* 2001; Fielder & Graw 2003; Turner-Walker & Jans 2008; Zhou & Bayard 2011; Hollund *et al.* 2012). Bacterial bioerosion in these samples would have been controlled by how far the body had decomposed before the grave became inundated (Hollund *et al.* 2012). These results supported inferences regarding the interaction between bacterial bone bioerosion and putrefaction, but indicated that histological preservation of bone cannot be related to funerary treatment within remains from anaerobic environments (Turner-Walker & Jans 2008; Hollund *et al.* 2012).

The next factor that dictated the extent of bacterial bioerosion was whether a bone originated from a Black Death cemetery. Samples of bone from the Royal Mint Black Death graveyard demonstrated lower levels of bacterial bioerosion than the rest of the study sample. A proportion of the Black Death skeletons had been recovered in variable stages of articulation and it was likely that there had been a delay between death and burial of these individuals. Rapid soft tissue loss of unburied bodies associated with skeletonising insects would have ensured that the bones of these individuals experienced lower levels of putrefaction and related bacterial bioerosion. The link between Black Death contexts and histological preservation provided the first indication of a relationship between early funerary treatment and bacterial bone bioerosion within this study.

The final factor that influenced the level of bacterial bioerosion and one of the main factors that dictated the presence of bacterial attack was phase. Bones from Later Prehistoric contexts were more likely to be free from bacterial bioerosion or demonstrate variably elevated levels of histological preservation when compared to samples of Historical bone. When the neonatal, anoxic-deposited and Black Death samples were excluded, 98% of Historical samples demonstrated bacterial bioerosion. The significantly leptokurtic distribution of Historical Whole OHI scores around zero indicated that these samples invariably demonstrated high levels of bacterial attack. There was no significant variation in patterns of bacterial bioerosion between bones from different Historical sites. All significant variation in bacterial bioerosion

amongst the Historical samples was explained by neonatal, anoxic-deposited and Black Death bones. These patterns of bacterial bioerosion were consistent with extensive exposure to putrefaction encouraged by immediate burial after death (Rodriguez & Bass 1983; 1985; Nielsen-Marsh & Hedges 2000; Jans *et al.* 2004; Nielsen-Marsh *et al.* 2007; Hollund *et al.* 2012).

When the anoxic-deposited, neonatal and Black Death remains were removed from the distribution the three hypotheses set out above regarding the relationship between bacterial bioerosion and funerary treatment were all supported by the data. This result suggested that bacterial bone bioerosion within the remaining samples reflected the extent to which early post treatment exposed the bones to putrefaction in a way that was consistent with experimental and forensic studies of decomposition.

The consistency in levels of bacterial attack amongst the Historical samples suggested that recorded and unrecorded factors that would have varied amongst this population had enacted no significant effect on the progression of putrefactive bone bioerosion. These variables included post-neonatal age-at-death, sex, burial soil, wrapping/clothing, coffin burial, seasonality, burial depth, microbiome, diet, health, infection, trauma and archaeological age. The common theme amongst some of these variables was that they have been observed to affect the rate rather than extent of cadaveric decomposition. This result emphasised that patterns of bacterial bioerosion are likely to reflect a small range of early *post mortem* processes that significantly reduce bone exposure to soft tissue putrefaction, such as dismemberment, sub-aerial exposure, evisceration or mummification (Jans *et al.* 2004). Signatures of bacterial bioerosion could not be confidently used to infer practise of treatments that have a more nuanced effect on bodily decomposition, such as coffin burial.

It was expected that state of skeletal articulation and archaeological phase would provide the best proxies of funerary treatment within the Later Prehistoric remains. There were no consistent significant differences in bacterial bioerosion that related to these features. However, deviations in patterns of bacterial attack that separated the Later Prehistoric remains from the Historical samples could be explained by phase-specific patterns of bacterial bioerosion. It was likely that the variability in funerary treatment practised within and between single sites from similar periods as well as the equifinality of certain processes had distorted phase-specific patterns of bacterial bioerosion. The lack of correlation between patterns of bacterial bioerosion and state of skeletal articulation was attributed to the incorrect assumption that burial was the only way in which an articulated skeleton could persist into the

archaeological record. Variation in bacterial bioerosion with Later Prehistoric phase supported the notion that bacterial bioerosion varied with funerary treatment in a predictable way.

Histological investigation of mummified bone suggested that these types of remains consistently demonstrate high levels of microstructural preservation. This result was consistent with previous histological characterisations of mummified bone (Weinstein *et al.* 1981; Thompson & Cowen 1984; Brothwell & Bourke 1995; Hess *et al.* 1998). Bones from mummies represent the only ancient articulated remains that consistently demonstrated high levels of histological preservation. The results from the partially preserved Derrycashel bog body provided the first evidence that mummified bone is not immune to enteric bacterial tunnelling. Haphazard techniques of preservation will allow some visceral bacteria to escape and bioerode the bone microstructure. The evidence for a signature of histological preservation associated with mummification supported the link between bacterial bioerosion and funerary treatment.

Confirmation of the hypotheses and the supporting evidence provided by the analysis of bacterial bioerosion positively answered all the research questions posed by the current study. Analysis of bacterial bioerosion via microscopic examination of archaeological bone would be useful in identifying funerary rites that significantly affected the level of putrefaction a bone experienced. This method would work best when combined with forensic studies of decomposition and the accompanying taphonomic evidence from the site.

9.2 FUNGAL TUNNELLING

Fungal tunnelling occurred alongside non-Wedl MFD within a small proportion of the bones used in the current study. This Wedl tunnelling was concentrated on small areas of bone microstructure that had not been altered by bacterial attack. Wedl tunnelling was found most commonly within bones from cave environments. This relationship was consistent with forensic studies of decomposition within caves, which had indicated that fungi are heavily involved in later bodily decay (Terrell-Nield & MacDonald 1997).

The results suggested that Wedl bioerosion is more likely to occur within bone that decomposed in an open environment post skeletonisation. Therefore, there could be a loose relationship between fungal tunnelling and certain modes of early *post mortem* treatment. The presence of Wedl tunnelling within a bone sample would suggest that it may have previously

lain on the ground surface or within an open chamber such as a cave, pit or ossuary. Fungal tunnelling may be of limited use in reconstructing taphonomic histories and funerary treatment in a small proportion of archaeological remains. Analysis of fungal tunnelling provided limited positive answers to the research questions posed by the current study.

9.3 Persistence of the Periosteal Surface

The periosteal surface persisted in the majority of specimens included in the current study sample, regardless of the extent to which the internal microstructure had been bioeroded. This result contributed to previous observations that the periosteal outer circumferential lamellar bone is immune to bacterial exploitation (Hedges 2002; Jans *et al.* 2004). The best explanation for this pattern was the low number of osteons that are found within circumferential lamellar bone. Osteons represent the point of entry for invading enteric microorganisms and their absence from periosteal circumferential lamellar bone would restrict bacterial colonisation. The results from the current study suggested that periosteal loss was associated with extrinsic variables that would have affected external macroscopic cortical erosion such as sediment movement and/or weathering. Periosteal loss or degradation may be useful in inferring early *post mortem* treatment as part of holistic studies of cortical erosion that are used in identifying processes such as sub-aerial exposure.

9.4 Accelerated Collagen Hydrolysis

Evidence for collagen loss by accelerated chemical hydrolysis in the form of non-biotic loss of collagen birefringence was found within a small number of bone sampled for the current study. One of the bones that had been degraded in this manner had come from a skeleton that had been covered in slaked lime. Evidence for accelerated collagen hydrolysis within this sample supported previous suggestions that the increase in environmental pH produced by liming promotes bone collagen loss by accelerating hydrolytic reactions (Smith *et al.* 2002). A number of other samples that had lost collagen birefringence showed signs of having been exposed to low levels of heat. Prolonged exposure to moderately high temperatures for long durations is known to accelerate hydrolysis (Collins *et al.* 1995; Smith *et al.* 2002; Abdel-Maksoud 2010). The exact circumstances that were responsible for the accelerated hydrolysis

within the remainder of the remains used in this study could not be discerned. Microscopic evidence for accelerated collagen hydrolysis can be linked with specific conditions or treatments such as high environmental pH or low level heat treatment in a small proportion of archaeological bones.

9.5 VISUAL DIAGENETIC CHANGES

Orange staining and orange inclusions were found in the majority of bones sampled for the current project. The occurrence and extent of these features were correlated with one another and with orange infiltrations. Infiltrations had most often formed in situations where inclusions had become so compacted that the material had spilled out of natural porosities into the surrounding microstructure, although these features sometimes appeared unaccompanied by inclusions. The frequencies of these diagenetic changes were associated with the type of burial soil. Staining was observed most commonly within peripheral areas of bone that would have been in contact with the sediment. Orange visual diagenetic changes most likely represented manifestations of interactions between the bone and iron oxides in the soil (Garland 1987; Grupe & Dreses-Werringloer 1993; Schultz 1997; Hollund *et al.* 2012).

Previous studies had indicated that that discolouration of the bone microstructure by iron oxides may be indicative early decomposition of a body within an anoxic environment that would have interfered with putrefactive bone bioerosion (Turner-Walker & Jans 2008; Hollund *et al.* 2012). The ubiquity of orange microstructural changes combined with the lack of association between these features and measures of bacterial bioerosion or environmental anoxia suggested that orange diagenetic changes were not representative of anoxic environments within the study sample used in the current project. The likelihood that orange microstructural changes represented accumulations of iron oxides that had infiltrated the bone over the course of its deposition suggested that these features are not useful in inferring aspects of funerary treatment. However, all three forms of orange diagenetic change had been influenced by charnelling practices. Charnel bones demonstrated lower levels of orange visual diagenetic features than articulated remains. The only conceivable explanation for this pattern was that past disinterment of the charnel bones had reduced their interactions with the burial environment. This result suggested that microscopic detection of anomalous differences in visual diagenetic changes across site assemblages could be used to suggest that certain bones had interacted with the burial environment to a lesser extent and may have been previously

disinterred. However, the overriding and varied influence of burial soil on visual diagenetic changes meant that any inferences of anthropogenic *post mortem* treatment would be tenuous.

Small numbers of bone samples demonstrated different categories of staining and inclusions. The occurrence of grey inclusions within remains from particular environments supported the relationship between these features and the constitution of the burial environment. There was a loose association between brown staining and decaying organic matter, which was consistent with the conclusions of previous studies that brown staining represents infiltration of bone by humic acids (Garland 1987; Grupe & Dreses-Werringloer 1993; van Klinken & Hedges 1995; Schultz 1997; Shahack-Gross *et al.* 1997). The presence of such staining could be useful for inferring the former presence of organic grave goods or wrappings that had surrounded parts of the body. Yellow microstructural discolouration was related to specific environmental conditions and treatments such as chemical contamination or burning (Hanson & Cain 2005; Squires *et al.* 2011). The infrequent occurrence of these features and uncertainty regarding their exact aetiology meant that they would have limited use in reconstructions of funerary treatment. In rare cases visual diagenetic features were indicative of specific taphonomic processes and may therefore be of limited use in inferring funerary treatment as a supplement to other diagenetic changes.

9.6 INTERPRETATION OF FUNERARY TREATMENT

The third research question referred to the types of funerary treatments that can be inferred from measures of bone diagenesis. This factor was partly addressed by the discussion of the various diagenetic parameters but was most apparent within interpretations of the funerary treatment at Later Prehistoric sites. The following section provides a summary of the funerary treatments that were inferred to have been practised within particular phases of the British Later Prehistoric, which gives some indications as to the kinds of practices that can be discerned using the histological method when it is combined with other taphonomic information.

9.6.1 Neolithic

All of the Neolithic remains sampled originated from caves or chambered tombs. The measures of bone diagenesis combined with the taphonomic evidence suggested that funerary activity usually involved the interment of whole bodies within these contexts. Skeletons had been disarticulated and comingled by subsequent manipulation, selective removal of skeletal elements and disturbance during successive interment. Similar signatures of bone diagenesis were found within assemblages from caves and tombs, which suggested that bodily decomposition had proceeded similarly within bodies that had been placed within these separate contexts.

The histological and taphonomic evidence relating to two individuals from Carsington Pasture Cave suggested that they had been dismembered soon after death, which may have represented a deviant form of treatment. A combination of dating, taphonomic and histological evidence from of the Frälsegården assemblage suggested that there had been a shift in funerary practices from rites that resembled those practised at other Neolithic sites to a form of treatment that attempted to maintain an individual's bodily form (Sjögren, in prep.).

9.6.2 Bronze Age

The results from the Bronze Age skeletons suggested that a proportion of the articulated bodies had been immediately buried after death. The Early Bronze Age remains that had been interred within pits underneath a round barrow at South Dumpton Down had been successively deposited, manipulated and disturbed (Perkins 1994). Evidence for this practise was confined to this site and may have represented a continuation of Neolithic successive interment and manipulation within a mortuary context (Gibson 2007).

The diagenetic signatures of the rest of the Bronze Age articulated remains were consistent with previous mummification (Weinstein *et al.* 1981; Thompson & Cowen 1984; Stout 1986; Brothwell & Bourke 1995; Hess *et al.* 1998; Parker Pearson *et al.* 2005). These histological signatures were only found consistently amongst articulated remains that dated to the Bronze Age. The influence of phase on the presence of bacterial bioerosion suggested that phase-specific treatment was most likely to be responsible for the lack of bacterial bioerosion within samples of Bronze Age bone from anoxic environments. Variations in signatures of bacterial bioerosion amongst these formerly-mummified Bronze Age remains suggested that methods

of preservation were likely to have been variably successful. Many of the samples from partially articulated and disarticulated Bronze Age bones also demonstrated diagenetic signatures that were consistent with mummification. These diagenetic signatures could have been produced through disarticulation by sub-aerial exposure. The Cladh Hallan mummies had been constructed out of the partially articulated parts of several individuals (Parker Pearson 2005; Hanna *et al.* 2012). Prior mummification of both disarticulated and articulated Bronze Age remains represented the most elegant interpretation of the evidence. The samples that demonstrated a mummification diagenetic signature originated from Bronze Age assemblages that were widely dispersed around the country and provided the first indications that mummification may have been practised on a widespread scale in Britain during this period.

9.6.3 Iron Age

The analysis of the Iron Age individuals suggested that treatment varied little between different archaeological sites. The results suggested the Iron Age remains had been subjected to one of two practices: immediate burial of a corpse followed by exhumation, manipulation and retention of remains or decomposition within an open or covered pit, followed by manipulation, curation and burial. It was possible that all remains had been placed originally within an open or covered pit before being variably manipulated and buried. Histological and taphonomic information from one of the disarticulated bones from Danebury suggested that this individual had decomposed on the ground surface before the bones were heated at a low temperature. This individual may have been afforded a deviant form of funerary treatment.

9.7 SUMMARY

In sum, bacterial bioerosion was the best measure of bone diagenesis that addressed the research aims of this study regarding the relationship between diagenesis and funerary treatment. This parameter was mostly influenced by whether a bone originated from a neonatal individual or an anoxic environment. When neonatal and anoxic-deposited bones were excluded there was a detectable relationship between measures of bacterial bioerosion and phase that was strong enough to be identified by the microscopic examination of most archaeological bones. Bacterial bioerosion of bone varied with phase in a way that would be

expected based on forensic studies of cadaveric decomposition and the ways in which the dead were known to have been treated in Historical and Later Prehistoric periods. Bacterial bone bioerosion of post-neonatal remains that decomposed in aerobic environments reflected the extent to which certain funerary treatment exposed the bones to putrefactive attack. Examples of rites that are likely to produce characteristic signatures of bacterial bioerosion include dismemberment, evisceration, sub-aerial exposure, inhumation, and mummification. Analysis of bacterial bioerosion is a useful tool in interpreting early *post mortem* treatment of human remains when combined with information regarding bodily decomposition in different situations and holistic study of the accompanying taphonomic evidence.

The relationship between other measures of bone diagenesis and funerary treatment were not as strong or definable. The appearance of these features could be loosely associated with particular depositional situations or treatments, but only amongst a small number of samples. Measures of fungal tunnelling, periosteal bone loss and collagen birefringence can usefully supplement interpretations of funerary treatments from bacterial bioerosion. The recognition of these sorts of diagenetic changes is important for discussions of variations of bacterial bioerosion.

The most common forms of visual diagenetic change to the bone microstructure related to properties of the burial environment. These features did not demonstrate a significant relationship with early *post mortem* processes and are likely to be of little use in reconstructions of funerary treatments. However, interpretations of early *post mortem* treatment that incorporate bacterial bioerosion should also include measures of visual diagenetic features to ensure that variation in bacterial attack was not related to interactions between the bone and the burial sediment. Microscopic characterisation of diagenetic changes to bone, particularly bacterial bone bioerosion, would be useful in discerning treatments responsible for disarticulated assemblages of bone. Analysis of bone diagenesis would also be useful for identifying hidden or unexpected forms of funerary treatment, such as previous mummification (Parker Pearson *et al.* 2005).

9.8 LIMITATIONS

9.8.1 Anoxic Environments & Neonates

The primary limitation of the current study with regards to the research aims was that bacterial bone bioerosion did not primarily correlate with funerary treatment. The associations between bacterial bioerosion, deposition within an anoxic environment and neonatal age meant that bacterial bioerosion could not be explained by specific funerary processes within a large proportion of the study sample. The use of bone histology as a method of inferring funerary treatment would not be applicable to all archaeological remains. However, it would be expected that future studies of archaeological bone diagenesis would be able to compensate for the effects of neonatal remains and anoxic environments. Most burial contexts included in the current study were not anoxic throughout the duration of deposition, and so it would be expected that the problem of previous anoxia would apply to bones from only a limited number of sites.

The variable anoxia associated with episodic waterlogging meant that bone assemblages had been designated as having originated from an anoxic environment when it was unlikely that every grave had been inundated during bodily decomposition. Distributions of measures of diagenesis amongst these samples could not be used as a reliable model of bone diagenesis within an anaerobic environment. Diagenesis and levels of histological preservation would be expected to vary between cemeteries depending on frequency and duration of episodic inundations as well as the layout of the burial ground.

Another consequence of the methodology was that bodies that were classified as having originated from aerobic environments may have decomposed under anoxic conditions. Characteristics of burial sediment can change over time, particularly in areas where the water table has been artificially altered (Turner-Walker & Jans 2008). Anoxic decomposition would have to be the primary explanation applied to archaeological remains that demonstrated an elevated pattern of histological preservation. The likelihood that an assemblage decomposed within an intermittently-anoxic environment could not be determined through examination of the bone microstructure alone and would have to be discerned through scrutiny of the accompanying environmental and taphonomic evidence. This conclusion further emphasised that histological analysis of archaeological bone is not a stand-alone method and must be combined with other environmental and taphonomic information if it is to be of use.

9.8.2 Nature of Analysis

The differences in patterns of bacterial bioerosion between Historical and Later Prehistoric remains varied in a way that would be predicted based on knowledge regarding their likely treatment and forensic models of cadaveric decomposition (Rodriguez & Bass 1983; 1985; Mann *et al.* 1990; Nielsen-Marsh *et al.* 2000; Campobasso *et al.* 2001; Jans *et al.* 2004; Nielsen-Marsh *et al.* 2007; Vas 2011; Zhou & Bayard 2011). Funerary treatment represented the best explanation for these patterns of variation, but correlation between funerary processes and diagenetic parameters were inferred rather than observed directly. The use of archaeological remains meant that not all variables could be controlled and there was a possibility that patterns of bacterial bone bioerosion were influenced by variation in underlying variables that had not been considered. The results from the Black Death skeletons, cut-marked bone, the limed skeleton and the mummified remains provided supporting evidence that bacterial bioerosion varied predictably with treatment and reduced the likelihood that alternative factors were responsible for variation in bacterial bioerosion amongst the Later Prehistoric samples, but this possibility could not be dismissed completely.

9.8.3 Measures of Diagenesis

The failure to access facilities used to characterise crystallinity of bone samples meant that one of the primary measures of bone diagenesis was not included in the current study. The lack of measures of the mineral phase did not significantly impact on the ability to address the main aims but the conclusions of the current study could not be taken as a complete representation of how bone diagenesis can be used to determine funerary treatment. The absence of crystallinity values limited interpretive strength and breadth of the current study. Changes to the bone mineral phase that are not caused by biological alteration are usually promoted by corrosive environments or heat treatment (Sillen & Parkington 1996; Hedges *et al.* 1995; Van Klinken & Hedges 1995; Hiller *et al.* 2004; Thompson 2004; Hiller & Wess 2006; Reiche *et al.* 2003; Nielsen-Marsh *et al.* 2007; Smith *et al.* 2007; Thompson *et al.* 2009; Squires *et al.* 2011; Thompson *et al.* 2013). Measures of mineral change may have helped to refine explanations of diagenetic patterns within certain assemblages. For instance, crystallinity values could have helped to determine whether burning was responsible for the deviant diagenetic signature of Deposit 130 from Danebury. Knowledge of bone mineral alteration would also have helped to confirm whether the categories of soil type used in the current study represented real

differences in sediment that affected mechanisms of bone diagenesis (Nielsen-Marsh *et al.* 2007; Smith *et al.* 2007).

9.8.4 Sample Sizes

The small samples sizes involved with comparisons of specific site assemblages meant that results produced were sometimes questionable. Small sample size became pertinent when it was considered that the baseline Historical distribution covered all possible Whole OHI scores. There was a chance that elevated levels of histological preservation could have occurred as a result of skewed sampling of variation attributable to burial. Low sample sizes made it difficult to determine whether site-specific deviations from the Historical baseline model were a result of treatment or low numbers of samples having produced a skewed distribution. The site-specific interpretations of mortuary processes within small assemblages were hazardous when taken by themselves.

Bones from Bronze Age contexts routinely demonstrated levels of histological preservation that deviated from the Historical baseline sample. However, the small sample sizes at particular sites meant that the possibility that the results represented a skewed representation of natural variation could not be discounted. The likelihood that these patterns had occurred by chance was significantly reduced when the same deviations were found within the Bronze Age assemblage considered as a whole. It was fortunate that many of the site-specific interpretations of funerary treatment were borne out when remains were collated into larger phase-specific groups.

9.8.5 Diagenetic Signatures of Funerary Rites

It should be emphasised that the results of the current study suggested that bacterial bioerosion of bone would only be useful for identifying funerary processes that had a significant impact on the extent of putrefaction experienced by a bone. Microstructural analysis of archaeological bones would only be useful for identifying a restricted number of treatments. The problem of wide variation in bacterial bioerosion within bones from individuals that had been buried was compounded by the likelihood that signatures of bacterial bioerosion associated with other types of funerary ritual consisted of spectra rather

than absolute values. The diagenetic effects of particular funerary treatments are likely to overlap. This overlap would disrupt attempts to interpret mortuary rites. Whilst there is evidence that sub-aerial exposure of a body consistently produces low levels of bacterial bone bioerosion, the range of possible attack would probably overlap with the attack observed within bones from buried bodies.

There is also the problem of equifinality of particular funerary processes. Certain discrete funerary treatments could expose bones to similar levels of putrefaction and produce similar patterns of bone diagenesis. This problem was particularly apparent within attempts to determine treatment of Neolithic remains from caves and tombs. Deposition of bodies in certain indoor contexts was likely to produce patterns of bacterial bioerosion that were similar to those encouraged by primary burial.

Inferences of funerary treatment from the diagenetic signatures of single samples would be extremely tenuous. Any inferences would have to be based on probabilities regarding which form of treatment most often causes the specific signature of attack, combined with a holistic analysis of the accompanying taphonomic evidence. Ideally, the use of histological analysis to infer funerary treatment would be applied to a decent sample size across a single site to determine whether the distribution of diagenetic signatures across multiple bone samples was consistent with a particular form of treatment. Variability in diagenetic signatures of different funerary rites would be problematic at sites where multiple mortuary processes were practised contemporaneously. Interpretations of funerary treatment using these methods would represent likelihoods rather than certainties. These conclusions further emphasise that histological analysis cannot be used alone as a tool for deducing early *post mortem* taphonomy, and has to be assimilated into an holistic taphonomic analysis of a site. In certain cases, it might be necessary to put forward several possible explanations for the diagenetic and taphonomic evidence.

9.8.6 Measures of Burial Soil

The inconsistencies in the records of the burial sediments at the sites included in the current study meant that this variable could only be defined in crude terms. It could not be determined whether this variable was representative of soil properties that would have affected bone diagenesis. Visual diagenetic alterations to bone microstructure such as staining, inclusions and infiltrations have been associated with properties of the surrounding burial

matrix (Garland 1987; Grupe & Dreses-Werringloer 1993; Van Klinken & Hedges 1995; Schultz 1997; Shahack-Gross *et al.* 1997). The correlations between measures of these features and burial soil within the current study suggested that the categories of sediment related to real properties of the burial environment that affected interactions between the sediment and the bone. The lack of correlation between precise measures of soil properties and bacterial bioerosion recorded by previous studies suggested it was unlikely that variation in bacterial attack within the current study sample was attributable to variations in burial context that had not been encompassed by the measurements of sediment type (Nielsen-Marsh & Hedges 2000; Nielsen-Marsh *et al.* 2007; Smith *et al.* 2007). The lack of variation in bacterial bioerosion amongst the bones from the dispersed Historical sites also suggested that sediment was unlikely to account for significant variation in bacterial bioerosion, although the uncertainties regarding the appropriateness of soil type categories meant that the results of the current study could not be used to infer that soil properties never have any effect on bacterial bone bioerosion.

The inability to record soil pH weakened the conclusions of the current study as it was possible that inequalities in the pH of soils at sites from different archaeological phases were responsible for significant variation in measures of bone diagenesis. However, it was improbable that soil pH of the dispersed sites used in the current study would have varied in a way that produced the observed patterns of bone diagenesis. Measures of bone diagenesis often varied significantly across bones from single sites where burial sediment was consistent. The likelihood that soil pH varied little over the sites that were included in this study further suggested that this factor was unlikely to have interfered with bone diagenesis amongst the current study sample. Previous studies of archaeological bone diagenesis that included precise measures of soil pH failed to identify correlations between this factor and bone diagenesis within non-acidic environments (Nielsen-Marsh *et al.* 2007; Smith *et al.* 2007). However, the results of the current study could not be used to state with certainty that soil pH has no effect on the measures of bone diagenesis in contexts that were not significantly acidic.

9.8.7 Visual Diagenetic Changes

One of the weaknesses of the thin section light microscopy method was that whilst it could be used to detect the presence and extent of visual diagenetic changes, it was limited in discerning their constitution. It was impossible to identify discriminating aspects of visual

diagenetic changes beyond simple differences such as colour. Identification of the materials responsible for these type of changes had to be achieved through comparison against similar phenomenon described by previous studies (Garland 1987; Grupe & Dreses-Werringloer 1993; Van Klinken & Hedges 1995; Schultz 1997; Shahack-Gross *et al.* 1997; Hollund *et al.* 2012). It was possible that subtle differences in visual diagenetic features had been missed by the techniques used in the current study. Such differences may have been indicative of materials associable with environments or treatments that were responsible for particular diagenetic trajectories (Turner-Walker & Jans 2008; Hollund *et al.* 2012). The conclusions of the current study relating to the simplistic categories of staining, inclusions and infiltrations remained valid. However, more precise methods of analysis that would provide a more nuanced separation of categories might find that variability in these features can produce more useful information about taphonomic processes. It was likely that the current study only captured a small fraction of the possible visual diagenetic features that can appear within archaeological bone. Therefore the results cannot be used to suggest that the study of visual diagenetic changes are never of any value to reconstructions of early taphonomic processes. Future studies of bone diagenesis would have to consider the potential impact of these features.

9.8.8 Skeletal Element

The results of the current study were limited slightly by the inclusion of samples from varying skeletal elements, as it has not been determined how bone diagenesis might vary within different types of bones (Hanson & Buikstra 1987; Jans *et al.* 2004). There was no consistent significant variation in bone diagenesis with skeletal element amongst the study sample used in the current project. There was a possibility that measures of diagenesis varied subtly between skeletal elements, but that sample sizes were too low to capture this diversity. The exclusive use of long bones and the low occurrences of particular skeletal elements meant that the results could not be used to refute the suggestion that bone diagenesis varies with skeletal element. The validity of future studies of the relationship between bone diagenesis and funerary treatment would be uncertain unless they were concentrated on a specific skeletal element or controlled for potential discrepancies between different bones.

9.8.9 Mummification

Only two samples of bone from mummified individuals were included in the current study. The histological preservation of both of these samples was consistent with the few previous histomorphological studies of bone from mummies and suggested that there was a characteristic signature of histological bone preservation associated with mummification (Weinstein *et al.* 1981; Thompson & Cowen 1984; Stout 1986; Brothwell & Bourke 1995; Hess *et al.* 1998; Parker Pearson *et al.* 2005). However, the small number of samples analysed meant that the notion of a digenetic signature of mummification was still uncertain. Mummified bone is likely to demonstrate variable levels of histological preservation depending on the method of preservation. The highly degraded bone sample from one of the Cladh Hallan individuals suggested that high levels of histological preservation within bones of mummies might be a tendency rather than an absolute (Parker Pearson *et al.* 2005).

9.8.10 Archaeological Remains from Different Parts of the World

The samples used in the Primary analysis were limited to bones obtained from temperate zones. Environmental factors have a greater effect on bodily decomposition in parts of the world where climatic conditions are more extreme (Rodriguez & Bass 1983; 1985; Galloway *et al.* 1989; Parson 2003; Dent *et al.* 2004; Congram 2008; Parks 2011; Vass 2011; Voss *et al.* 2011; Zhou & Bayard 2011). The increased influence of environmental variables on decomposition may reduce or negate the effectiveness of measures of bone diagenesis, particularly bacterial bioerosion, in reconstructions of funerary treatment. In addition, there could be a host of unknown factors that affect the origin and extent of bone diagenesis in different parts of the world, such as variations in soil bacteria or geology.

9.8.11 Chronological Age

The results suggested that seven-thousand-year-old histologically well-preserved and poorly-preserved bones from temperate Europe are just as likely to survive into the archaeological record (Hedges 2002). However, only histologically well-preserved bones survive over geological timescales (Hedges 2002; Trueman & Martill 2002). These observations suggest whilst bacterial bioerosion does not appear to affect bone survival over archaeological

timescales, histologically poorly-preserved bones are unlikely to persist beyond a critical chronological threshold. Patterns of diagenesis found within Palaeolithic and older human bones may not provide a representative distribution of bone diagenesis as it relates to early taphonomic processes.

9.9 FUTURE RESEARCH

9.9.1 Refining and Corroborating Findings

The conclusions of the current research could be corroborated and refined through analysis of the same or comparable study samples using alternative measures of bone diagenesis. Reanalysis of some of the bones using techniques that measure bone mineral change would aid in refining interpretive models of diagenesis (Sillen & Parkington 1996; Hedges *et al.* 1995; Van Klinken & Hedges 1995; Hiller *et al.* 2004; Thompson 2004; Hiller & Wess 2006; Reiche *et al.* 2003; Nielsen-Marsh *et al.* 2007; Smith *et al.* 2007; Thompson *et al.* 2009; Squires *et al.* 2011; Thompson *et al.* 2013). These analyses would provide a better impression of how far diagenetic changes to bone can be used in the reconstructions of taphonomic histories.

Examination of bone microstructure using precise techniques such as SEM would allow for better discrimination of visual diagenetic changes (Turner-Walker & Syversen 2002; Turner-Walker 2008; Turner-Walker & Jans 2008; Hollund *et al.* 2012). Reanalysis of remains using this technique would help to refine conclusions regarding how staining, inclusions and infiltrations can be used to reconstruct taphonomic processes. SEM can be used to identify features such as framboidal pyrite, which would help to determine whether patterns of bacterial bioerosion in certain samples were a product of anthropogenic treatment or decomposition under anoxic conditions (Turner-Walker & Jans 2008; Hollund *et al.* 2012). Anoxic decomposition produces localised acidic demineralisation of bone microstructure. A combination of measures of crystallinity and SEM could be used to develop a system of determining whether or not a body was likely to have previously decomposed within an anoxic environment (Hollund *et al.* 2012).

Another possible method of corroborating the results of the current study would be to examine signatures of diagenesis within remains from multi-period single sites where funerary treatment varied between phases. For instance, it would be pertinent to compare diagenetic signatures of bones from a British site where there was evidence for both Historical burial and

Later Prehistoric variable manipulation of the dead. Such a study would provide a microcosm of the research presented here whilst reducing potential variation in environmental factors that may have interfered with bone diagenesis.

Further testing of the correlation between bacterial bioerosion and funerary treatment could involve the histological examination of archaeological bones from varied societies that were known to have practised processes that would have reduced the levels of putrefaction a bone experienced. However, the best way to corroborate the results of the current study would be through the analysis of bone diagenesis within experimentally-deposited human bodies or analogous pig carcasses (Fernández-Jalvo *et al.* 2010; White 2009). This methodology would be the only way of testing correlations between funerary treatment and bone diagenesis directly. White's (2010) study followed this model, but only examined a small range of treatments over a limited time period.

9.9.2 Neonatal Remains

The results from the neonatal remains suggested that the skeletons of stillborn individuals may be identifiable within the archaeological record. Histological analysis of archaeological bone could be used to calculate rates of still-births within past populations and identify societies where this category of remains had been afforded a deviant form of treatment (Finlay 2000). Such studies would provide greater clarity of the causes of infant mortality as well as the perception and treatment of stillborn individuals in the past.

9.9.3 Waterlogged Environments

Further research is required into the exact effects of intermittently-waterlogged environments on bacterial bone bioerosion (Turner-Walker & Jans 2008; Hollund *et al.* 2012). It was likely that variation in bacterial bioerosion within bones from waterlogged cemeteries used in the current study was related to the timing of inundation. It would be pertinent to investigate this inference further by examining whether variation in bacterial bioerosion amongst articulated remains from a seasonally-waterlogged cemetery conformed to expected patterns. For instance, it would be predicted that bone from deeper burials would be more likely to demonstrate heightened levels of histological preservation. Establishing how bacterial bone bioerosion varies within waterlogged cemeteries may help to determine how far funerary

treatment can be discerned within remains recovered from these sorts of environments. Such studies might also be informative as to predictive models of histological preservation within remains obtained from particular contexts.

9.9.4 Funerary Treatment

One of the primary ways in which the results of the current study could instigate future research would be in studies of the types of funerary rites that were practiced in the past. Microstructural analysis would be particularly useful for investigating prehistoric funerary rites at sites where practices are disputed or ambiguous. Microstructural analysis of archaeological bone could be particularly helpful in determining mechanisms of disassembly amongst disarticulated skeletons.

The most obvious application of the results of the current study would be a direct examination of British Bronze Age remains to establish whether there is further evidence that this civilisation routinely mummified their dead (Parker Pearson *et al.* 2005; 2007). The results from the Bronze Age and mummified samples suggested that histological analysis may provide a consistent method of determining whether an archaeological skeleton had been previously mummified. The primary indications of the veracity of the mummification hypothesis presented in the results of the current study suggested that it would also be worth investigating whether evidence for a similar rite could be located at Bronze Age or earlier sites on the European continent. The result emphasised how the histological method could help to identify funerary treatments that would otherwise have been hidden and revolutionise perceptions on how particular societies treated their dead.

Any investigations into the practise of mummification in Bronze Age Britain would have to be accompanied by further histological examination of mummified material. Investigations into the histological preservation of bog body bone conducted as part of the current study established potential mechanisms responsible for the loss of the skeleton within bog-deposited remains that retain preserved soft tissues. Further investigation into similar samples might help to determine the mechanisms behind the variability in preservation of human remains from these environments. Examination of bone from mummies that had been preserved using variable techniques would help to establish the range of diagenetic outcomes associated with these remains and determine how far the mode of preservation could be discerned by histological examination of bone. To the same end, it would also be relevant to

examine the histology of skeletons that were likely to have been previously mummified, such as the Guanche bodies of Tenerife or skeletal Peruvian mummy bundles (Aufderheide 2003).

9.9.5 Black Death

Another possible future research direction suggested by the results of the current study could be an exploration of the relationship between bone diagenesis and the Plague. It would be pertinent to investigate whether the differential pattern of bacterial bioerosion observed amongst the skeletons from the Black Death graves occurred as a result of delayed burial or the way that the associated pathogen interfered with processes of decomposition. One way of doing this might be to investigate the remains from the Royal Mint Black Death graves in further detail to determine whether disarticulated skeletons were more likely to display deviant patterns of bacterial bioerosion. If no such pattern was observed then it would have to be considered that the pathogen itself was the factor that had affected bodily decomposition and bone bioerosion. If bacterial bioerosion was related to the delay between death and burial, then inferences could be made regarding the individuals from Black Death cemeteries that were likely to have been local or transported from further afield. Temporal variation in patterns of bacterial bioerosion might be indicative of reactions to the escalation of the epidemic that caused fluctuations in the period between death and burial. In an eventuality where bacterial bioerosion was related to the Black Death pathogen, histomorphological studies of medieval remains could be used to identify Plague-affected individuals that had been afforded a conventional burial within an established cemetery.

9.9.6 Remaining Variation in Bacterial Bioerosion

It was not the intention of the current study to identify all of the factors responsible for variation in bone diagenesis and bacterial bone bioerosion in particular. One of the questions that was left unanswered by the current project was what factor was responsible for the little variation in bacterial bioerosion observed amongst the Historical baseline assemblage. It would be important to determine what other factors might influence bone exposure to putrefaction in to ensure that variation in bacterial bioerosion is not mistaken for differences encouraged by early *post mortem* treatment. For instance it would be interesting to examine patterns of bacterial bioerosion within archaeological populations where there was evidence

for circumstances that would have had an extreme effect on microbiome health. Starvation represents one process that would be expected to substantially alter the abundance of gut microbiota. It would be relevant to investigate patterns of bacterial bioerosion amongst a Historical cemetery population dating to a period of famine. If bacterial bone bioerosion was related to microbiome, histological preservation of bone amongst famine assemblages would be higher than what would be expected from an inhumed Historical articulated population.

9.9.7 Faunal Assemblages

The current study focussed on diagenesis of archaeological human bones in order to avoid the taphonomic and microstructural complexities involved with examining bone from variable species. The same types of bioerosion observed within human bones have been found within archaeological and modern bones of several different species and are likely to have a similar enteric aetiology (Nicholson 1996; Davis 1997; Nielsen-Marsh & Hedges 2000; Hedges 2002; Jans *et al.* 2004; Fernández-Jalvo *et al.* 2010; Hollund *et al.* 2012). It would be expected that diagenetic changes association with interactions between human bone and the burial environment would be similar amongst faunal assemblages. Histological examination of bone could be used as part of holistic taphonomic analyses in determining early *post mortem* treatment of all species recovered from archaeological sites.

9.9.8 Biomolecular Yield

Histological preservation of bone has been variably linked to the survival or organic molecules such as aDNA (Hagelburg *et al.* 1991; Grupe 1995; Colson *et al.* 1997; Cipollaro *et al.* 1998; Gardner 1999; Geigl 2002; Götherström *et al.* 2002; Haynes *et al.* 2002; Rollo *et al.* 2002; Devièse *et al.* 2010). The exact relationship between the histological preservation of bone and aDNA yield in particular is unclear (Collins *et al.* 2009; Ottoni *et al.* 2009). Loss of bone protein does not necessarily equate to a direct corresponding loss of DNA (Collins *et al.* 2009; Otoni *et al.* 2009). Nevertheless, the conclusion of the current study may present some counter-intuitive notions with regards to the likely success of attempts to extract biomolecules from archaeological bone.

Most discussions of biomolecular preservation are concerned with environmental conditions and time, but the results of the present study emphasise the role of early cultural practices

(Perry *et al.* 1988; Grupe 1995; Mays 1998; Geigl 2002; Götherström *et al.* 2002; Haynes *et al.* 2002; Rollo *et al.* 2002; Devièse *et al.* 2010). There is no doubt that biomolecules degrade at a predictable rate that is dependent on the environmental conditions (Collins *et al.* 1995). However, the extent of biomolecular survival in bone recovered from a temperate site, as dictated by histological preservation, should not vary with archaeological time and would be dependent on the way an individual was treated after death. The oldest bones used in this study, those from the Mesolithic Havnø shell midden, demonstrated some of the highest levels of histological preservation of any assemblage, and may be more viable for biomolecular analysis than the majority of the remains excavated from British Historical contexts. The inhibitory effects of waterlogged environments on bacterial bone bioerosion suggested that biomolecular studies are also likely to be more successful when applied to bones from anoxic contexts, discounting those environments such as peat bogs whose properties obstruct aDNA amplification in other ways (Painter 1995). The bones of neonates, which in the past have been considered to be most susceptible to diagenetic processes, may retain the largest potential for survival of biogenic molecules (Buckberry 2000).

Periosteal circumferential lamellar bone represents the part of a specimen that is most likely to have survived into the archaeological. However, this area of bone is undesirable for use in biomolecular sampling, as it is more susceptible to contamination (Hagelburg *et al.* 1991). The internal third of a bone cross-section consistently demonstrated the next-highest levels of histological preservation, and could present the best choice for sampling. The indications that bacterial bone bioerosion was dependent upon porosity dictated by ratios of cortical and trabecular and osteonal density indicated that biomolecular sampling would be best targeted on compact bone that is unlikely to have undergone significant remodelling. Further research related to the conclusions of this study could help to refine protocols for optimising biomolecular yield from archaeological bone.

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11 APPENDIX 1: REGRESSION MODELS

11.1 WHOLE OHI

11.1.1 Whole OHI Ordinal Regression Model 1

Case Processing Summary

		N	Marginal Percentage
Whole OHI	0	42	35.9%
	1	23	19.7%
	2	20	17.1%
	3	14	12.0%
	4	6	5.1%
	5	12	10.3%
Anoxic	Absent	106	90.6%
	Present	11	9.4%
Phase	Later Prehistoric	40	34.2%
	Historical	77	65.8%
Soil Type	Clay	30	25.6%
	Gravel	55	47.0%
	Sand	16	13.7%
	Silt	13	11.1%
Cave	Open	3	2.6%
	Non-Cave	114	97.4%
	Cave	3	2.6%
Black Death	Non-Black Death	95	81.2%
	Black Death	22	18.8%
State	Articulated	99	84.6%
	Disarticulated	18	15.4%
Charnel	Non-Charnel	115	98.3%
	Charnel	2	1.7%
Sex	Male	62	53.0%
	Female	55	47.0%
Age Range	Juvenile	12	10.3%
	Adult	105	89.7%
Valid		117	100.0%
Missing		184	
Total		301	

Model Fitting Information

Model	-2 Log Likelihood	Chi-Square	df	Sig.
Intercept Only	237.061			
Final	198.169	38.893	11	.000

Link function: Logit.

Goodness-of-Fit

	Chi-Square	df	Sig.
Pearson	164.914	159	.358
Deviance	134.422	159	.922

Link function: Logit.

Pseudo R-Square

Cox and Snell	.283
Nagelkerke	.294
McFadden	.102

Link function: Logit.

Parameter Estimates

		Estimate	Std. Error	Wald	df	Sig.	95% Confidence Interval	
							Lower Bound	Upper Bound
Threshold	[WholeHI = 0]	-3.765	1.786	4.443	1	.035	-7.265	-.264
	[WholeHI = 1]	-2.765	1.770	2.442	1	.118	-6.233	.703
	[WholeHI = 2]	-1.821	1.759	1.072	1	.301	-5.270	1.627
	[WholeHI = 3]	-.919	1.758	.273	1	.601	-4.365	2.528
	[WholeHI = 4]	-.321	1.765	.033	1	.856	-3.780	3.139
Location	[Anoxic=0]	-4.073	.917	19.711	1	.000	-5.870	-2.275
	[Anoxic=1]	0[a]	.	.	0	.	.	.
	[Phase2Num2=1]	2.544	.621	16.799	1	.000	1.327	3.760
	[Phase2Num2=2]	0[a]	.	.	0	.	.	.
	[StandardSoilNum=1]	-.324	1.270	.065	1	.799	-2.813	2.165
	[StandardSoilNum=2]	1.021	1.298	.618	1	.432	-1.524	3.565
	[StandardSoilNum=3]	.826	1.282	.415	1	.519	-1.686	3.338
	[StandardSoilNum=4]	-.102	1.173	.008	1	.931	-2.401	2.197
	[StandardSoilNum=5]	0[a]	.	.	0	.	.	.
	[Cave=0]	0[a]	.	.	0	.	.	.
	[Cave=1]	0[a]	.	.	0	.	.	.
	[BD=0]	-1.415	.518	7.459	1	.006	-2.431	-.400
	[BD=1]	0[a]	.	.	0	.	.	.
	[State2Num=1.00]	.363	.694	.273	1	.601	-.998	1.724
	[State2Num=2.00]	0[a]	.	.	0	.	.	.
	[Charnel=0]	.253	1.416	.032	1	.858	-2.521	3.028
	[Charnel=1]	0[a]	.	.	0	.	.	.
	[SexNum=1]	.111	.358	.096	1	.756	-.590	.813
	[SexNum=2]	0[a]	.	.	0	.	.	.
	[AgeRange4Num=3.00]	-.704	.604	1.356	1	.244	-1.888	.481
	[AgeRange4Num=4.00]	0[a]	.	.	0	.	.	.

Link function: Logit.

a. This parameter is set to zero because it is redundant.

Test of Parallel Lines[a]

Model	-2 Log Likelihood	Chi-Square	df	Sig.
Null Hypothesis	198.169			
General	213.926[b]	.[c]	44	.

The null hypothesis states that the location parameters (slope coefficients) are the same across response categories.

a. Link function: Logit.

b. The log-likelihood value cannot be further increased after maximum number of step-halving.

c. The log-likelihood value of the general model is smaller than that of the null model. This is because convergence cannot be attained or ascertained in estimating the general model. Therefore, the test of parallel lines cannot be performed.

11.1.2 Whole OHI Ordinal Regression Model 2

Case Processing Summary

		N	Marginal Percentage
Whole OHI	0	127	42.2%
	1	45	15.0%
	2	51	16.9%
	3	23	7.6%
	4	15	5.0%
	5	40	13.3%
Anoxic	Absent	261	86.7%
	Present	40	13.3%
Phase	Later Prehistoric	93	30.9%
	Historical	208	69.1%
Soil Type	Clay	159	52.8%
	Gravel	65	21.6%
	Sand	24	8.0%
	Silt	35	11.6%
Cave	Open	18	6.0%
	Non-Cave	279	92.7%
	Cave	22	7.3%
Black Death	Non-Black Death	276	91.7%
	Black Death	25	8.3%
State	Articulated	238	79.1%
	Disarticulated	63	20.9%
Charnel	Non-Charnel	213	70.8%
	Charnel	88	29.2%
Age Range	Neonate	31	10.3%
	Child	23	7.6%
	Juvenile	39	13.0%
	Adult	208	69.1%
Valid		301	100.0%
Missing		0	
Total		301	

Model Fitting Information

Model	-2 Log Likelihood	Chi-Square	df	Sig.
Intercept Only	430.806			
Final	347.557	83.249	13	.000

Link function: Logit.

Goodness-of-Fit

	Chi-Square	df	Sig.
Pearson	260.832	202	.003
Deviance	207.651	202	.378

Link function: Logit.

Pseudo R-Square

Cox and Snell	.242
Nagelkerke	.253
McFadden	.088

Link function: Logit.

Parameter Estimates

		Estimate	Std. Error	Wald	df	Sig.	95% Confidence Interval	
							Lower Bound	Upper Bound
Threshold	[WholeHI = 0]	-3.247	.815	15.865	1	.000	-4.844	-1.649
	[WholeHI = 1]	-2.529	.806	9.839	1	.002	-4.108	-.949
	[WholeHI = 2]	-1.590	.798	3.967	1	.046	-3.154	-.025
	[WholeHI = 3]	-1.031	.797	1.670	1	.196	-2.593	.532
	[WholeHI = 4]	-.562	.799	.495	1	.482	-2.129	1.005
Location	[Anoxic=0]	-2.064	.367	31.574	1	.000	-2.784	-1.344
	[Anoxic=1]	0[a]	.	.	0	.	.	.
	[Phase2Num2=1]	1.543	.446	11.962	1	.001	.669	2.418
	[Phase2Num2=2]	0[a]	.	.	0	.	.	.
	[StandardSoilNum=1]	-1.126	1.206	.871	1	.351	-3.491	1.239
	[StandardSoilNum=2]	-.916	1.233	.552	1	.457	-3.332	1.500
	[StandardSoilNum=3]	-.034	1.209	.001	1	.977	-2.405	2.336
	[StandardSoilNum=4]	-1.562	1.094	2.040	1	.153	-3.706	.581
	[StandardSoilNum=5]	0[a]	.	.	0	.	.	.
	[Cave=0]	.477	1.070	.199	1	.656	-1.620	2.575
	[Cave=1]	0[a]	.	.	0	.	.	.
	[BD=0]	-1.456	.483	9.077	1	.003	-2.404	-.509
	[BD=1]	0[a]	.	.	0	.	.	.
	[State2Num=1.00]	.413	.465	.790	1	.374	-.498	1.325
	[State2Num=2.00]	0[a]	.	.	0	.	.	.
	[Charnel=0]	-.078	.390	.040	1	.841	-.843	.687
	[Charnel=1]	0[a]	.	.	0	.	.	.
	[AgeRange4Num=1.00]	2.183	.442	24.399	1	.000	1.317	3.050
	[AgeRange4Num=2.00]	-1.020	.503	4.110	1	.043	-2.006	-.034
	[AgeRange4Num=3.00]	-.186	.344	.292	1	.589	-.859	.488
	[AgeRange4Num=4.00]	0[a]	.	.	0	.	.	.

Link function: Logit.

a. This parameter is set to zero because it is redundant.

Test of Parallel Lines[a]

Model	-2 Log Likelihood	Chi-Square	df	Sig.
Null Hypothesis	347.557			
General	194.784[b]	152.773[c]	52	.000

The null hypothesis states that the location parameters (slope coefficients) are the same across response categories.

a. Link function: Logit.

b. The log-likelihood value cannot be further increased after maximum number of step-halving.

c. The Chi-Square statistic is computed based on the log-likelihood value of the last iteration of the general model. Validity of the test is uncertain.

11.1.3 Whole OHI Ordinal Regression Model 3

Case Processing Summary

		N	Marginal Percentage
Whole OHI	0	127	42.2%
	1	45	15.0%
	2	51	16.9%
	3	23	7.6%
	4	15	5.0%
	5	40	13.3%
Anoxic	Absent	261	86.7%
	Present	40	13.3%
Phase	Later Prehistoric	93	30.9%
	Historical	208	69.1%
Black Death	Non-Black Death	276	91.7%
	Black Death	25	8.3%
Age Range	Neonate	31	10.3%
	Child	23	7.6%
	Juvenile	39	13.0%
	Adult	208	69.1%
Valid		301	100.0%
Missing		0	
Total		301	

Model Fitting Information

Model	-2 Log Likelihood	Chi-Square	df	Sig.
Intercept Only	268.441			
Final	197.629	70.812	6	.000

Link function: Logit.

Goodness-of-Fit

	Chi-Square	df	Sig.
Pearson	95.281	64	.007
Deviance	96.888	64	.005

Link function: Logit.

Pseudo R-Square

Cox and Snell	.210
Nagelkerke	.219
McFadden	.075

Link function: Logit.

Parameter Estimates

		Estimate	Std. Error	Wald	df	Sig.	95% Confidence Interval	
							Lower Bound	Upper Bound
Threshold	[WholeHI = 0]	-2.979	.512	33.897	1	.000	-3.982	-1.976
	[WholeHI = 1]	-2.274	.499	20.764	1	.000	-3.252	-1.296
	[WholeHI = 2]	-1.356	.488	7.724	1	.005	-2.313	-.400
	[WholeHI = 3]	-.818	.487	2.821	1	.093	-1.773	.137
	[WholeHI = 4]	-.373	.491	.576	1	.448	-1.334	.589
Location	[Anoxic=0]	-1.924	.338	32.406	1	.000	-2.587	-1.262
	[Anoxic=1]	0[a]	.	.	0	.	.	.
	[Phase2Num2=1]	1.101	.257	18.413	1	.000	.598	1.604
	[Phase2Num2=2]	0[a]	.	.	0	.	.	.
	[BD=0]	-1.431	.405	12.484	1	.000	-2.225	-.637
	[BD=1]	0[a]	.	.	0	.	.	.
	[AgeRange4Num=1.00]	2.028	.376	29.032	1	.000	1.290	2.766
	[AgeRange4Num=2.00]	-1.082	.490	4.884	1	.027	-2.042	-.122
	[AgeRange4Num=3.00]	-.229	.334	.468	1	.494	-.885	.427
	[AgeRange4Num=4.00]	0[a]	.	.	0	.	.	.

Link function: Logit.

a. This parameter is set to zero because it is redundant.

Test of Parallel Lines[a]

Model	-2 Log Likelihood	Chi-Square	df	Sig.
Null Hypothesis	197.629			
General	180.704[b]	16.925[c]	24	.852

The null hypothesis states that the location parameters (slope coefficients) are the same across response categories.

a. Link function: Logit.

b. The log-likelihood value cannot be further increased after maximum number of step-halving.

c. The Chi-Square statistic is computed based on the log-likelihood value of the last iteration of the general model. Validity of the test is uncertain.

11.1.4 Whole OHI Paired Ordinal Regression Models

11.1.4.1 Age Range & Anoxia

Case Processing Summary

		N	Marginal Percentage
Whole OHI	0	127	42.2%
	1	45	15.0%
	2	51	16.9%
	3	23	7.6%
	4	15	5.0%
	5	40	13.3%
Anoxic	Absent	261	86.7%
	Present	40	13.3%
Age Range	Neonate	31	10.3%
	Child	23	7.6%
	Juvenile	39	13.0%
	Adult	208	69.1%
Valid		301	100.0%
Missing		0	
Total		301	

Model Fitting Information

Model	-2 Log Likelihood	Chi-Square	df	Sig.
Intercept Only	177.390			
Final	131.061	46.329	4	.000

Link function: Logit.

Goodness-of-Fit

	Chi-Square	df	Sig.
Pearson	52.637	31	.009
Deviance	57.832	31	.002

Link function: Logit.

Pseudo R-Square

Cox and Snell	.143
Nagelkerke	.149
McFadden	.049

Link function: Logit.

Parameter Estimates

		Estimate	Std. Error	Wald	df	Sig.	95% Confidence Interval	
							Lower Bound	Upper Bound
Threshold	[WholeHI = 0]	-1.580	.313	25.488	1	.000	-2.193	-.967
	[WholeHI = 1]	-.917	.305	9.040	1	.003	-1.515	-.319
	[WholeHI = 2]	-.052	.300	.030	1	.863	-.640	.537
	[WholeHI = 3]	.466	.304	2.356	1	.125	-.129	1.061
	[WholeHI = 4]	.897	.312	8.280	1	.004	.286	1.508
Location	[Anoxic=0]	-1.363	.313	18.945	1	.000	-1.976	-.749
	[Anoxic=1]	0[a]	.	.	0	.	.	.
	[AgeRange4Num=1.00]	1.526	.355	18.475	1	.000	.830	2.221
	[AgeRange4Num=2.00]	-1.345	.481	7.822	1	.005	-2.288	-.402
	[AgeRange4Num=3.00]	-.472	.329	2.065	1	.151	-1.117	.172
	[AgeRange4Num=4.00]	0[a]	.	.	0	.	.	.

Link function: Logit.

a. This parameter is set to zero because it is redundant.

Test of Parallel Lines[a]

Model	-2 Log Likelihood	Chi-Square	df	Sig.
Null Hypothesis	131.061			
General	120.841[b]	10.220[c]	16	.855

The null hypothesis states that the location parameters (slope coefficients) are the same across response categories.
a. Link function: Logit.
b. The log-likelihood value cannot be further increased after maximum number of step-halving.
c. The Chi-Square statistic is computed based on the log-likelihood value of the last iteration of the general model. Validity of the test is uncertain.

11.1.4.2 Age Range & Black Death

Case Processing Summary

		N	Marginal Percentage
Whole OHI	0	127	42.2%
	1	45	15.0%
	2	51	16.9%
	3	23	7.6%
	4	15	5.0%
	5	40	13.3%
Age Range	Neonate	31	10.3%
	Child	23	7.6%
	Juvenile	39	13.0%
	Adult	208	69.1%
Black Death	Non-Black Death	276	91.7%
	Black Death	25	8.3%
Valid		301	100.0%
Missing		0	
Total		301	

Model Fitting Information

Model	-2 Log Likelihood	Chi-Square	df	Sig.
Intercept Only	135.420			
Final	106.457	28.963	4	.000

Link function: Logit.

Goodness-of-Fit

	Chi-Square	df	Sig.
Pearson	38.141	21	.012
Deviance	37.601	21	.014

Link function: Logit.

Pseudo R-Square

Cox and Snell	.092
Nagelkerke	.096
McFadden	.031

Link function: Logit.

Parameter Estimates

		Estimate	Std. Error	Wald	df	Sig.	95% Confidence Interval	
							Lower Bound	Upper Bound
Threshold	[WholeHI = 0]	-.941	.364	6.704	1	.010	-1.654	-.229
	[WholeHI = 1]	-.303	.360	.711	1	.399	-1.008	.402
	[WholeHI = 2]	.519	.361	2.066	1	.151	-.189	1.226
	[WholeHI = 3]	1.004	.366	7.514	1	.006	.286	1.722
	[WholeHI = 4]	1.417	.375	14.274	1	.000	.682	2.152
Location	[AgeRange4Num=1.00]	1.537	.356	18.654	1	.000	.840	2.235
	[AgeRange4Num=2.00]	-1.268	.481	6.950	1	.008	-2.210	-.325
	[AgeRange4Num=3.00]	-.283	.325	.761	1	.383	-.920	.353
	[AgeRange4Num=4.00]	0[a]	.	.	0	.	.	.
	[BD=0]	-.649	.378	2.949	1	.086	-1.390	.092
	[BD=1]	0[a]	.	.	0	.	.	.

Link function: Logit.
a. This parameter is set to zero because it is redundant.

Test of Parallel Lines[a]

Model	-2 Log Likelihood	Chi-Square	df	Sig.
Null Hypothesis	106.457			
General	97.255	9.202	16	.905

The null hypothesis states that the location parameters (slope coefficients) are the same across response categories.
a. Link function: Logit.

11.1.4.3 Age Range & Phase

Case Processing Summary

		N	Marginal Percentage
Whole OHI	0	127	42.2%
	1	45	15.0%
	2	51	16.9%
	3	23	7.6%
	4	15	5.0%
	5	40	13.3%
Age Range	Neonate	31	10.3%
	Child	23	7.6%
	Juvenile	39	13.0%
	Adult	208	69.1%
Phase	Later Prehistoric	93	30.9%
	Historical	208	69.1%
Valid		301	100.0%
Missing		0	
Total		301	

Model Fitting Information

Model	-2 Log Likelihood	Chi-Square	df	Sig.
Intercept Only	160.050			
Final	130.213	29.837	4	.000

Link function: Logit.

Goodness-of-Fit

	Chi-Square	df	Sig.
Pearson	47.710	31	.028
Deviance	50.527	31	.015

Link function: Logit.

Pseudo R-Square

Cox and Snell	.094
Nagelkerke	.099
McFadden	.032

Link function: Logit.

Parameter Estimates

		Estimate	Std. Error	Wald	df	Sig.	95% Confidence Interval	
							Lower Bound	Upper Bound
Threshold	[WholeHI = 0]	-.209	.159	1.711	1	.191	-.521	.104
	[WholeHI = 1]	.424	.161	6.958	1	.008	.109	.739
	[WholeHI = 2]	1.240	.176	49.593	1	.000	.895	1.585
	[WholeHI = 3]	1.728	.193	80.516	1	.000	1.350	2.105
	[WholeHI = 4]	2.148	.212	102.827	1	.000	1.733	2.563
Location	[AgeRange4Num=1.00]	1.563	.358	19.081	1	.000	.862	2.264
	[AgeRange4Num=2.00]	-1.298	.481	7.289	1	.007	-2.241	-.356
	[AgeRange4Num=3.00]	-.277	.323	.732	1	.392	-.910	.357
	[AgeRange4Num=4.00]	0[a]	.	.	0	.	.	.
	[Phase2Num2=1]	.481	.231	4.356	1	.037	.029	.933
	[Phase2Num2=2]	0[a]	.	.	0	.	.	.

Link function: Logit.

a. This parameter is set to zero because it is redundant.

Test of Parallel Lines[a]

Model	-2 Log Likelihood	Chi-Square	df	Sig.
Null Hypothesis	130.213			
General	108.919[b]	21.295[c]	16	.167

The null hypothesis states that the location parameters (slope coefficients) are the same across response categories.

a. Link function: Logit.

b. The log-likelihood value cannot be further increased after maximum number of step-halving.

c. The Chi-Square statistic is computed based on the log-likelihood value of the last iteration of the general model. Validity of the test is uncertain.

11.1.4.4 Phase & Anoxia

Case Processing Summary

		N	Marginal Percentage
Whole OHI	0	127	42.2%
	1	45	15.0%
	2	51	16.9%
	3	23	7.6%
	4	15	5.0%
	5	40	13.3%
Phase	Later Prehistoric	93	30.9%
	Historical	208	69.1%
Anoxic	Absent	261	86.7%
	Present	40	13.3%
Valid		301	100.0%
Missing		0	
Total		301	

Model Fitting Information

Model	-2 Log Likelihood	Chi-Square	df	Sig.
Intercept Only	97.475			
Final	70.025	27.450	2	.000

Link function: Logit.

Goodness-of-Fit

	Chi-Square	df	Sig.
Pearson	11.787	13	.545
Deviance	11.974	13	.530

Link function: Logit.

Pseudo R-Square

Cox and Snell	.087
Nagelkerke	.091
McFadden	.029

Link function: Logit.

Parameter Estimates

		Estimate	Std. Error	Wald	df	Sig.	95% Confidence Interval	
							Lower Bound	Upper Bound
Threshold	[WholeHI = 0]	-1.467	.300	23.978	1	.000	-2.054	-.880
	[WholeHI = 1]	-.822	.292	7.894	1	.005	-1.395	-.249
	[WholeHI = 2]	.004	.288	.000	1	.990	-.560	.567
	[WholeHI = 3]	.488	.290	2.834	1	.092	-.080	1.057
	[WholeHI = 4]	.889	.297	8.958	1	.003	.307	1.472
Location	[Phase2Num2=1]	.691	.234	8.736	1	.003	.233	1.150
	[Phase2Num2=2]	0[a]	.	.	0	.	.	.
	[Anoxic=0]	-1.534	.320	23.057	1	.000	-2.161	-.908
	[Anoxic=1]	0[a]	.	.	0	.	.	.

Link function: Logit.

a. This parameter is set to zero because it is redundant.

Test of Parallel Lines[a]

Model	-2 Log Likelihood	Chi-Square	df	Sig.
Null Hypothesis	70.025			
General	61.622	8.402	8	.395

The null hypothesis states that the location parameters (slope coefficients) are the same across response categories.
a. Link function: Logit.

11.1.4.5 Phase & Black Death

Case Processing Summary

		N	Marginal Percentage
Whole OHI	0	127	42.2%
	1	45	15.0%
	2	51	16.9%
	3	23	7.6%
	4	15	5.0%
	5	40	13.3%
Phase	Later Prehistoric	93	30.9%
	Historical	208	69.1%
Black Death	Non-Black Death	276	91.7%
	Black Death	25	8.3%
Valid		301	100.0%
Missing		0	
Total		301	

Model Fitting Information

Model	-2 Log Likelihood	Chi-Square	df	Sig.
Intercept Only	75.737			
Final	67.924	7.813	2	.020

Link function: Logit.

Goodness-of-Fit

	Chi-Square	df	Sig.
Pearson	12.467	8	.132
Deviance	11.597	8	.170

Link function: Logit.

Pseudo R-Square

Cox and Snell	.026
Nagelkerke	.027
McFadden	.008

Link function: Logit.

Parameter Estimates

		Estimate	Std. Error	Wald	df	Sig.	95% Confidence Interval	
							Lower Bound	Upper Bound
Threshold	[WholeHI = 0]	-.883	.363	5.935	1	.015	-1.594	-.173
	[WholeHI = 1]	-.265	.359	.544	1	.461	-.970	.439
	[WholeHI = 2]	.516	.361	2.045	1	.153	-.191	1.222
	[WholeHI = 3]	.967	.365	7.012	1	.008	.251	1.684
	[WholeHI = 4]	1.347	.373	13.041	1	.000	.616	2.078
Location	[Phase2Num2=1]	.508	.231	4.846	1	.028	.056	.960
	[Phase2Num2=2]	0[a]	.	.	0	.	.	.
	[BD=0]	-.786	.381	4.249	1	.039	-1.533	-.039
	[BD=1]	0[a]	.	.	0	.	.	.

Link function: Logit.
a. This parameter is set to zero because it is redundant.

Test of Parallel Lines[a]

Model	-2 Log Likelihood	Chi-Square	df	Sig.
Null Hypothesis	67.924			
General	56.326	11.597	8	.170

The null hypothesis states that the location parameters (slope coefficients) are the same across response categories.
a. Link function: Logit.

11.1.4.6 Anoxia & Black Death

Case Processing Summary

		N	Marginal Percentage
Whole OHI	0	127	42.2%
	1	45	15.0%
	2	51	16.9%
	3	23	7.6%
	4	15	5.0%
	5	40	13.3%
Black Death	Non-Black Death	276	91.7%
	Black Death	25	8.3%
Anoxic	Absent	261	86.7%
	Present	40	13.3%
Valid		301	100.0%
Missing		0	
Total		301	

Model Fitting Information

Model	-2 Log Likelihood	Chi-Square	df	Sig.
Intercept Only	93.688			
Final	68.758	24.931	2	.000

Link function: Logit.

Goodness-of-Fit

	Chi-Square	df	Sig.
Pearson	16.113	8	.041
Deviance	14.611	8	.067

Link function: Logit.

Pseudo R-Square

Cox and Snell	.079
Nagelkerke	.083
McFadden	.026

Link function: Logit.

Parameter Estimates

		Estimate	Std. Error	Wald	df	Sig.	95% Confidence Interval	
							Lower Bound	Upper Bound
Threshold	[WholeHI = 0]	-2.358	.489	23.250	1	.000	-3.317	-1.400
	[WholeHI = 1]	-1.709	.481	12.645	1	.000	-2.651	-.767
	[WholeHI = 2]	-.880	.472	3.478	1	.062	-1.805	.045
	[WholeHI = 3]	-.400	.471	.721	1	.396	-1.323	.523
	[WholeHI = 4]	-.008	.474	.000	1	.986	-.937	.920
Location	[BD=0]	-.866	.376	5.312	1	.021	-1.603	-.130
	[BD=1]	0[a]	.	.	0	.	.	.
	[Anoxic=0]	-1.419	.312	20.675	1	.000	-2.030	-.807
	[Anoxic=1]	0[a]	.	.	0	.	.	.

Link function: Logit.

a. This parameter is set to zero because it is redundant.

Test of Parallel Lines[a]

Model	-2 Log Likelihood	Chi-Square	df	Sig.
Null Hypothesis	68.758			
General	54.146	14.611	8	.067

The null hypothesis states that the location parameters (slope coefficients) are the same across response categories.

a. Link function: Logit.

11.2 PRESENCE OF BACTERIAL ATTACK

11.2.1 Presence of Bacterial Attack Binary Logistic Regression Model 1

Case Processing Summary

Unweighted Cases[a]		N	Percent
Selected Cases	Included in Analysis	117	38.9
	Missing Cases	184	61.1
	Total	301	100.0
Unselected Cases		0	.0
Total		301	100.0

a. If weight is in effect, see classification table for the total number of cases.

Omnibus Tests of Model Coefficients

		Chi-square	df	Sig.
Step 1	Step	27.826	11	.003
	Block	27.826	11	.003
	Model	27.826	11	.003

Model Summary

Step	-2 Log likelihood	Cox & Snell R Square	Nagelkerke R Square
1	49.554[a]	.212	.437

a. Estimation terminated at iteration number 20 because maximum iterations has been reached. Final solution cannot be found.

Hosmer and Lemeshow Test

Step	Chi-square	df	Sig.
1	2.078	7	.955

Contingency Table for Hosmer and Lemeshow Test

		Bacterial Tunnelling = Absent		Bacterial Tunnelling = Present		Total
		Observed	Expected	Observed	Expected	
Step 1	1	7	6.976	7	7.024	14
	2	2	2.468	11	10.532	13
	3	1	1.193	15	14.807	16
	4	1	.502	11	11.498	12
	5	1	.397	12	12.603	13
	6	0	.282	11	10.718	11
	7	0	.140	12	11.860	12
	8	0	.043	12	11.957	12
	9	0	.000	14	14.000	14

Classification Table[a]

	Observed		Predicted		
			Bacterial Tunnelling		Percentage Correct
			Absent	Present	
Step 1	Bacterial Tunnelling	Absent	4	8	33.3
		Present	2	103	98.1
	Overall Percentage				91.5

a. The cut value is .500

Variables in the Equation

		B	S.E.	Wald	df	Sig.	Exp(B)
Step 1[a]	Anoxic(1)	4.601	1.566	8.633	1	.003	99.551
	Phase2Num2(1)	-3.510	1.307	7.210	1	.007	.030
	StandardSoilNum			2.686	4	.612	
	StandardSoilNum(1)	-20.068	23205.424	.000	1	.999	.000
	StandardSoilNum(2)	-21.980	23205.424	.000	1	.999	.000
	StandardSoilNum(3)	-20.132	23205.424	.000	1	.999	.000
	StandardSoilNum(4)	-.179	25705.508	.000	1	1.000	.836
	BD(1)	.509	1.467	.121	1	.728	1.664
	State2Num(1)	.905	1.265	.511	1	.475	2.471
	Charnel(1)	.859	1.651	.271	1	.603	2.362
	SexNum(1)	-.179	.797	.050	1	.822	.836
	AgeRange4Num(1)	.204	1.309	.024	1	.876	1.226
	Constant	18.744	23205.424	.000	1	.999	138151848.363

a. Variable(s) entered on step 1: Anoxic, Phase2Num2, StandardSoilNum, BD, State2Num, Charnel, SexNum, AgeRange4Num.

11.2.2 Presence of Bacterial Attack Binary Logistic Regression Model 2

Case Processing Summary

Unweighted Cases[a]		N	Percent
Selected Cases	Included in Analysis	301	100.0
	Missing Cases	0	.0
	Total	301	100.0
Unselected Cases		0	.0
Total		301	100.0

a. If weight is in effect, see classification table for the total number of cases.

Omnibus Tests of Model Coefficients

		Chi-square	df	Sig.
Step 1	Step	80.476	13	.000
	Block	80.476	13	.000
	Model	80.476	13	.000

Model Summary

Step	-2 Log likelihood	Cox & Snell R Square	Nagelkerke R Square
1	151.634[a]	.235	.436

a. Estimation terminated at iteration number 20 because maximum iterations has been reached. Final solution cannot be found.

Hosmer and Lemeshow Test

Step	Chi-square	df	Sig.
1	9.012	7	.252

Contingency Table for Hosmer and Lemeshow Test

		Bacterial Tunnelling = Absent		Bacterial Tunnelling = Present		Total
		Observed	Expected	Observed	Expected	
Step 1	1	24	21.780	17	19.220	41
	2	5	8.534	32	28.466	37
	3	3	2.869	23	23.131	26
	4	5	3.418	34	35.582	39
	5	1	1.456	32	31.544	33
	6	0	.731	34	33.269	34
	7	1	.149	38	38.851	39
	8	0	.062	37	36.938	37
	9	0	.000	15	15.000	15

Classification Table[a]

	Observed		Predicted		
			Bacterial Tunnelling		Percentage Correct
			Absent	Present	
Step 1	Bacterial Tunnelling	Absent	14	25	35.9
		Present	3	259	98.9
	Overall Percentage				90.7

a. The cut value is .500

Variables in the Equation

		B	S.E.	Wald	df	Sig.	Exp(B)
Step 1[a]	Anoxic(1)	3.443	.982	12.297	1	.000	31.275
	Phase2Num2(1)	-2.437	.863	7.970	1	.005	.087
	StandardSoilNum			4.189	4	.381	
	StandardSoilNum(1)	2.585	18579.315	.000	1	1.000	13.257
	StandardSoilNum(2)	1.128	18579.315	.000	1	1.000	3.089
	StandardSoilNum(3)	1.167	18579.315	.000	1	1.000	3.214
	StandardSoilNum(4)	22.314	17142.102	.000	1	.999	4908017957.024
	Cave(1)	-2.722	18579.315	.000	1	1.000	.066
	BD(1)	.686	1.044	.431	1	.512	1.985
	State2Num(1)	.867	.833	1.083	1	.298	2.379
	Charnel(1)	-.976	.879	1.235	1	.267	.377
	AgeRange4Num			24.150	3	.000	
	AgeRange4Num(1)	-4.193	.868	23.320	1	.000	.015
	AgeRange4Num(2)	.310	1.203	.066	1	.797	1.363
	AgeRange4Num(3)	.014	.724	.000	1	.984	1.015
	Constant	.703	1.448	.236	1	.627	2.020

a. Variable(s) entered on step 1: Anoxic, Phase2Num2, StandardSoilNum, Cave, BD, State2Num, Charnel, AgeRange4Num.

11.2.3 Presence of Bacterial Attack Binary Logistic Regression Model 3

Case Processing Summary

Unweighted Cases[a]		N	Percent
Selected Cases	Included in Analysis	301	100.0
	Missing Cases	0	.0
	Total	301	100.0
Unselected Cases		0	.0
Total		301	100.0

a. If weight is in effect, see classification table for the total number of cases.

Omnibus Tests of Model Coefficients

		Chi-square	df	Sig.
Step 1	Step	50.014	5	.000
	Block	50.014	5	.000
	Model	50.014	5	.000

Model Summary

Step	-2 Log likelihood	Cox & Snell R Square	Nagelkerke R Square
1	182.096[a]	.153	.285

a. Estimation terminated at iteration number 6 because parameter estimates changed by less than .001.

Hosmer and Lemeshow Test

Step	Chi-square	df	Sig.
1	1.572	5	.905

Contingency Table for Hosmer and Lemeshow Test

		Bacterial Tunnelling = Absent		Bacterial Tunnelling = Present		Total
		Observed	Expected	Observed	Expected	
Step 1	1	17	16.112	16	16.888	33
	2	4	3.263	13	13.737	17
	3	9	11.216	63	60.784	72
	4	4	4.320	26	25.680	30
	5	1	1.023	24	23.977	25
	6	4	2.836	105	106.164	109
	7	0	.229	15	14.771	15

Classification Table[a]

	Observed		Predicted		
			Bacterial Tunnelling		Percentage Correct
			Absent	Present	
Step 1	Bacterial Tunnelling	Absent	7	32	17.9
		Present	2	260	99.2
	Overall Percentage				88.7

a. The cut value is .500

Variables in the Equation

		B	S.E.	Wald	df	Sig.	Exp(B)
Step 1[a]	Anoxic(1)	1.915	.574	11.144	1	.001	6.785
	Phase2Num2(1)	-1.933	.508	14.462	1	.000	.145
	AgeRange4Num			33.419	3	.000	
	AgeRange4Num(1)	-3.167	.566	31.276	1	.000	.042
	AgeRange4Num(2)	.542	1.073	.255	1	.613	1.720
	AgeRange4Num(3)	-.260	.605	.185	1	.667	.771
	Constant	1.708	.457	13.945	1	.000	5.517

a. Variable(s) entered on step 1: Anoxic, Phase2Num2, AgeRange4Num.

11.2.4 Presence of Bacterial Attack Paired Binary Logistic Regression Models

11.2.4.1 Age Range & Anoxia

Case Processing Summary

Unweighted Cases[a]		N	Percent
Selected Cases	Included in Analysis	301	100.0
	Missing Cases	0	.0
	Total	301	100.0
Unselected Cases		0	.0
Total		301	100.0

a. If weight is in effect, see classification table for the total number of cases.

Omnibus Tests of Model Coefficients

		Chi-square	df	Sig.
Step 1	Step	32.723	4	.000
	Block	32.723	4	.000
	Model	32.723	4	.000

Model Summary

Step	-2 Log likelihood	Cox & Snell R Square	Nagelkerke R Square
1	199.387[a]	.103	.192

a. Estimation terminated at iteration number 6 because parameter estimates changed by less than .001.

Hosmer and Lemeshow Test

Step	Chi-square	df	Sig.
1	2.564	3	.464

Contingency Table for Hosmer and Lemeshow Test

		Bacterial Tunnelling = Absent		Bacterial Tunnelling = Present		Total
		Observed	Expected	Observed	Expected	
Step 1	1	15	15.000	16	16.000	31
	2	6	6.585	28	27.415	34
	3	5	2.877	30	32.123	35
	4	13	13.826	168	167.174	181
	5	0	.713	20	19.287	20

Classification Table[a]

			Predicted		
			Bacterial Tunnelling		Percentage Correct
			Absent	Present	
Step 1	Bacterial Tunnelling	Absent	2	37	5.1
		Present	1	261	99.6
	Overall Percentage				87.4

a. The cut value is .500

Variables in the Equation

		B	S.E.	Wald	df	Sig.	Exp(B)
Step 1[a]	Anoxic(1)	1.053	.463	5.181	1	.023	2.867
	AgeRange4Num			30.543	3	.000	
	AgeRange4Num(1)	-2.331	.444	27.602	1	.000	.097
	AgeRange4Num(2)	.806	1.056	.582	1	.445	2.238
	AgeRange4Num(3)	-.063	.588	.011	1	.915	.939
	Constant	1.439	.425	11.482	1	.001	4.218

a. Variable(s) entered on step 1: Anoxic, AgeRange4Num.

11.2.4.2 Age Range & Phase

Case Processing Summary

Unweighted Cases[a]		N	Percent
Selected Cases	Included in Analysis	301	100.0
	Missing Cases	0	.0
	Total	301	100.0
Unselected Cases		0	.0
Total		301	100.0

a. If weight is in effect, see classification table for the total number of cases.

Omnibus Tests of Model Coefficients

		Chi-square	df	Sig.
Step 1	Step	38.877	4	.000
	Block	38.877	4	.000
	Model	38.877	4	.000

Model Summary

Step	-2 Log likelihood	Cox & Snell R Square	Nagelkerke R Square
1	193.233[a]	.121	.225

a. Estimation terminated at iteration number 6 because parameter estimates changed by less than .001.

Hosmer and Lemeshow Test

Step	Chi-square	df	Sig.
1	5.684	4	.224

Contingency Table for Hosmer and Lemeshow Test

		Bacterial Tunnelling = Absent		Bacterial Tunnelling = Present		Total
		Observed	Expected	Observed	Expected	
Step 1	1	15	15.000	16	16.000	31
	2	4	2.114	6	7.886	10
	3	11	12.369	63	61.631	74
	4	0	2.384	34	31.616	34
	5	8	6.631	126	127.369	134
	6	1	.502	17	17.498	18

Classification Table[a]

	Observed		Predicted		
			Bacterial Tunnelling		Percentage Correct
			Absent	Present	
Step 1	Bacterial Tunnelling	Absent	3	36	7.7
		Present	1	261	99.6
	Overall Percentage				87.7

a. The cut value is .500

Variables in the Equation

		B	S.E.	Wald	df	Sig.	Exp(B)
Step 1[a]	AgeRange4Num			33.136	3	.000	
	AgeRange4Num(1)	-2.729	.493	30.652	1	.000	.065
	AgeRange4Num(2)	.596	1.064	.314	1	.575	1.814
	AgeRange4Num(3)	-.290	.596	.236	1	.627	.749
	Phase2Num2(1)	-1.349	.420	10.320	1	.001	.259
	Constant	2.955	.358	68.160	1	.000	19.209

a. Variable(s) entered on step 1: AgeRange4Num, Phase2Num2.

11.2.4.3 Anoxia & Phase

Case Processing Summary

Unweighted Cases[a]		N	Percent
Selected Cases	Included in Analysis	301	100.0
	Missing Cases	0	.0
	Total	301	100.0
Unselected Cases		0	.0
Total		301	100.0

a. If weight is in effect, see classification table for the total number of cases.

Omnibus Tests of Model Coefficients

		Chi-square	df	Sig.
Step 1	Step	10.718	2	.005
	Block	10.718	2	.005
	Model	10.718	2	.005

Model Summary

Step	-2 Log likelihood	Cox & Snell R Square	Nagelkerke R Square
1	221.393[a]	.035	.065

a. Estimation terminated at iteration number 5 because parameter estimates changed by less than .001.

Hosmer and Lemeshow Test

Step	Chi-square	df	Sig.
1	.199	1	.656

Contingency Table for Hosmer and Lemeshow Test

		Bacterial Tunnelling = Absent		Bacterial Tunnelling = Present		Total
		Observed	Expected	Observed	Expected	
Step 1	1	9	9.000	31	31.000	40
	2	16	17.130	75	73.870	91
	3	14	12.870	156	157.130	170

Classification Table[a]

	Observed		Predicted		
			Bacterial Tunnelling		Percentage Correct
			Absent	Present	
Step 1	Bacterial Tunnelling	Absent	0	39	.0
		Present	0	262	100.0
	Overall Percentage				87.0

a. The cut value is .500

Variables in the Equation

		B	S.E.	Wald	df	Sig.	Exp(B)
Step 1[a]	Phase2Num2(1)	-1.041	.382	7.437	1	.006	.353
	Anoxic(1)	1.201	.465	6.679	1	.010	3.323
	Constant	1.301	.382	11.595	1	.001	3.674

a. Variable(s) entered on step 1: Phase2Num2, Anoxic.

11.3 WEDL TUNNELLING

11.3.1 Wedl Tunnelling Binary Logistic Regression Model 1

Case Processing Summary

Unweighted Cases[a]		N	Percent
Selected Cases	Included in Analysis	117	38.9
	Missing Cases	184	61.1
	Total	301	100.0
Unselected Cases		0	.0
Total		301	100.0

a. If weight is in effect, see classification table for the total number of cases.

Omnibus Tests of Model Coefficients

		Chi-square	df	Sig.
Step 1	Step	15.611	11	.156
	Block	15.611	11	.156
	Model	15.611	11	.156

Model Summary

Step	-2 Log likelihood	Cox & Snell R Square	Nagelkerke R Square
1	81.374[a]	.125	.222

a. Estimation terminated at iteration number 20 because maximum iterations has been reached. Final solution cannot be found.

Hosmer and Lemeshow Test

Step	Chi-square	df	Sig.
1	3.503	8	.899

Contingency Table for Hosmer and Lemeshow Test

		Wedl = Absent		Wedl = Present		Total
		Observed	Expected	Observed	Expected	
Step 1	1	11	11.000	0	.000	11
	2	12	11.645	0	.355	12
	3	13	13.244	1	.756	14
	4	10	10.116	1	.884	11
	5	10	10.806	2	1.194	12
	6	13	11.237	0	1.763	13
	7	12	12.229	3	2.771	15
	8	9	9.442	3	2.558	12
	9	7	7.650	4	3.350	11
	10	3	2.631	3	3.369	6

Classification Table[a]

	Observed		Predicted		
			Wedl		Percentage Correct
			Absent	Present	
Step 1	Wedl	Absent	99	1	99.0
		Present	15	2	11.8
	Overall Percentage				86.3

a. The cut value is .500

Variables in the Equation

		B	S.E.	Wald	df	Sig.	Exp(B)
Step 1[a]	Anoxic(1)	19.663	13253.478	.000	1	.999	346472470.200
	Phase2Num2(1)	.348	.877	.157	1	.692	1.416
	StandardSoilNum			4.741	4	.315	
	StandardSoilNum(1)	-2.930	1.674	3.062	1	.080	.053
	StandardSoilNum(2)	-3.054	1.754	3.034	1	.082	.047
	StandardSoilNum(3)	-4.104	1.901	4.660	1	.031	.017
	StandardSoilNum(4)	-2.104	1.469	2.051	1	.152	.122
	BD(1)	1.292	1.147	1.270	1	.260	3.641
	State2Num(1)	.504	1.006	.250	1	.617	1.655
	Charnel(1)	-.127	31134.721	.000	1	1.000	.881
	SexNum(1)	.733	.624	1.379	1	.240	2.081
	AgeRange4Num(1)	.380	.904	.177	1	.674	1.463
	Constant	-20.483	28172.969	.000	1	.999	.000

a. Variable(s) entered on step 1: Anoxic, Phase2Num2, StandardSoilNum, BD, State2Num, Charnel, SexNum, AgeRange4Num.

11.3.2 Wedl Tunnelling Binary Logistic Regression Model 2

Case Processing Summary

Unweighted Cases[a]		N	Percent
Selected Cases	Included in Analysis	301	100.0
	Missing Cases	0	.0
	Total	301	100.0
Unselected Cases		0	.0
Total		301	100.0

a. If weight is in effect, see classification table for the total number of cases.

Omnibus Tests of Model Coefficients

		Chi-square	df	Sig.
Step 1	Step	40.557	13	.000
	Block	40.557	13	.000
	Model	40.557	13	.000

Model Summary

Step	-2 Log likelihood	Cox & Snell R Square	Nagelkerke R Square
1	245.694[a]	.126	.205

a. Estimation terminated at iteration number 6 because parameter estimates changed by less than .001.

Hosmer and Lemeshow Test

Step	Chi-square	df	Sig.
1	5.149	8	.742

Contingency Table for Hosmer and Lemeshow Test

		Wedl = Absent		Wedl = Present		Total
		Observed	Expected	Observed	Expected	
Step 1	1	32	33.030	2	.970	34
	2	36	35.382	2	2.618	38
	3	32	29.807	1	3.193	33
	4	25	24.882	3	3.118	28
	5	26	25.423	5	5.577	31
	6	24	26.312	9	6.688	33
	7	19	18.196	4	4.804	23
	8	30	30.608	9	8.392	39
	9	19	17.891	8	9.109	27
	10	3	4.469	12	10.531	15

Classification Table[a]

	Observed		Predicted		
			Wedl		Percentage Correct
			Absent	Present	
Step 1	Wedl	Absent	240	6	97.6
		Present	42	13	23.6
	Overall Percentage				84.1

a. The cut value is .500

Variables in the Equation

		B	S.E.	Wald	df	Sig.	Exp(B)
Step 1[a]	Anoxic(1)	.041	.505	.007	1	.935	1.042
	Phase2Num2(1)	1.190	.667	3.180	1	.075	3.287
	StandardSoilNum			3.564	4	.468	
	StandardSoilNum(1)	-.234	1.402	.028	1	.868	.792
	StandardSoilNum(2)	.467	1.468	.101	1	.750	1.595
	StandardSoilNum(3)	-1.563	1.661	.885	1	.347	.210
	StandardSoilNum(4)	-.551	1.172	.221	1	.638	.576
	Cave(1)	-2.482	1.228	4.089	1	.043	.084
	BD(1)	.933	.851	1.201	1	.273	2.541
	State2Num(1)	.840	.740	1.290	1	.256	2.317
	Charnel(1)	-.914	.620	2.177	1	.140	.401
	AgeRange4Num			2.365	3	.500	
	AgeRange4Num(1)	-1.310	.860	2.320	1	.128	.270
	AgeRange4Num(2)	.018	.625	.001	1	.977	1.018
	AgeRange4Num(3)	-.048	.487	.010	1	.921	.953
	Constant	-.392	1.192	.108	1	.742	.676

a. Variable(s) entered on step 1: Anoxic, Phase2Num2, StandardSoilNum, Cave, BD, State2Num, Charnel, AgeRange4Num.

11.3.3 Wedl Tunnelling Binary Logistic Regression Model 3

Case Processing Summary

Unweighted Cases[a]		N	Percent
Selected Cases	Included in Analysis	301	100.0
	Missing Cases	0	.0
	Total	301	100.0
Unselected Cases		0	.0
Total		301	100.0

a. If weight is in effect, see classification table for the total number of cases.

Omnibus Tests of Model Coefficients

		Chi-square	df	Sig.
Step 1	Step	28.995	3	.000
	Block	28.995	3	.000
	Model	28.995	3	.000

Model Summary

Step	-2 Log likelihood	Cox & Snell R Square	Nagelkerke R Square
1	257.255[a]	.092	.150

a. Estimation terminated at iteration number 5 because parameter estimates changed by less than .001.

Hosmer and Lemeshow Test

Step	Chi-square	df	Sig.
1	.000	2	1.000

Contingency Table for Hosmer and Lemeshow Test

		Wedl = Absent		Wedl = Present		Total
		Observed	Expected	Observed	Expected	
Step 1	1	108	108.000	12	12.000	120
	2	60	60.000	11	11.000	71
	3	70	70.000	18	18.000	88
	4	8	8.000	14	14.000	22

Classification Table[a]

	Observed		Predicted		
			Wedl		Percentage Correct
			Absent	Present	
Step 1	Wedl	Absent	238	8	96.7
		Present	41	14	25.5
	Overall Percentage				83.7

a. The cut value is .500

Variables in the Equation

		B	S.E.	Wald	df	Sig.	Exp(B)
Step 1[a]	Phase2Num2(1)	.501	.447	1.253	1	.263	1.650
	Cave(1)	-2.256	.551	16.743	1	.000	.105
	Charnel(1)	-.839	.403	4.335	1	.037	.432
	Constant	.898	.611	2.157	1	.142	2.455

a. Variable(s) entered on step 1: Phase2Num2, Cave, Charnel.

11.3.4 Wedl Tunnelling Binary Logistic Regression Model 4

Case Processing Summary

Unweighted Cases[a]		N	Percent
Selected Cases	Included in Analysis	301	100.0
	Missing Cases	0	.0
	Total	301	100.0
Unselected Cases		0	.0
Total		301	100.0

a. If weight is in effect, see classification table for the total number of cases.

Omnibus Tests of Model Coefficients

		Chi-square	df	Sig.
Step 1	Step	27.757	2	.000
	Block	27.757	2	.000
	Model	27.757	2	.000

Model Summary

Step	-2 Log likelihood	Cox & Snell R Square	Nagelkerke R Square
1	258.494[a]	.088	.144

a. Estimation terminated at iteration number 5 because parameter estimates changed by less than .001.

Classification Table[a]

Observed			Predicted		
			Wedl		Percentage Correct
			Absent	Present	
Step 1	Wedl	Absent	238	8	96.7
		Present	41	14	25.5
	Overall Percentage				83.7

a. The cut value is .500

Variables in the Equation

		B	S.E.	Wald	df	Sig.	Exp(B)
Step 1[a]	Cave(1)	-2.548	.496	26.408	1	.000	.078
	Charnel	.630	.345	3.331	1	.068	1.878
	Constant	.560	.443	1.594	1	.207	1.750

a. Variable(s) entered on step 1: Cave, Charnel.

11.3.5 Wedl Tunnelling Binary Logistic Regression Model 5

Case Processing Summary

Unweighted Cases[a]		N	Percent
Selected Cases	Included in Analysis	301	100.0
	Missing Cases	0	.0
	Total	301	100.0
Unselected Cases		0	.0
Total		301	100.0

a. If weight is in effect, see classification table for the total number of cases.

Omnibus Tests of Model Coefficients

		Chi-square	df	Sig.
Step 1	Step	24.507	1	.000
	Block	24.507	1	.000
	Model	24.507	1	.000

Model Summary

Step	-2 Log likelihood	Cox & Snell R Square	Nagelkerke R Square
1	261.744[a]	.078	.127

a. Estimation terminated at iteration number 4 because parameter estimates changed by less than .001.

Classification Table[a]

	Observed		Predicted		
			Wedl		Percentage Correct
			Absent	Present	
Step 1	Wedl	Absent	238	8	96.7
		Present	41	14	25.5
	Overall Percentage				83.7

a. The cut value is .500

Variables in the Equation

		B	S.E.	Wald	df	Sig.	Exp(B)
Step 1[a]	Cave(1)	-2.318	.474	23.885	1	.000	.098
	Constant	.560	.443	1.594	1	.207	1.750

a. Variable(s) entered on step 1: Cave.

11.4 PERSISTENCE OF THE PERIOSTEAL SURFACE

11.4.1 Persistence of the Periosteal Surface Binary Logistic Regression Model 1

Case Processing Summary

Unweighted Cases[a]		N	Percent
Selected Cases	Included in Analysis	117	38.9
	Missing Cases	184	61.1
	Total	301	100.0
Unselected Cases		0	.0
Total		301	100.0

a. If weight is in effect, see classification table for the total number of cases.

Omnibus Tests of Model Coefficients

		Chi-square	df	Sig.
Step 1	Step	39.811	11	.000
	Block	39.811	11	.000
	Model	39.811	11	.000

Model Summary

Step	-2 Log likelihood	Cox & Snell R Square	Nagelkerke R Square
1	41.815[a]	.288	.574

a. Estimation terminated at iteration number 20 because maximum iterations has been reached. Final solution cannot be found.

Hosmer and Lemeshow Test

Step	Chi-square	df	Sig.
1	1.500	7	.982

Contingency Table for Hosmer and Lemeshow Test

		Periosteal Surface = Absent		Periosteal Surface = Present		Total
		Observed	Expected	Observed	Expected	
Step 1	1	8	8.000	5	5.000	13
	2	3	3.532	10	9.468	13
	3	2	1.046	10	10.954	12
	4	0	.423	13	12.577	13
	5	0	.000	16	16.000	16
	6	0	.000	13	13.000	13
	7	0	.000	9	9.000	9
	8	0	.000	11	11.000	11
	9	0	.000	17	17.000	17

Classification Table[a]

	Observed		Predicted		
			Periosteal Surface		Percentage Correct
			Absent	Present	
Step 1	Periosteal Surface	Absent	5	8	38.5
		Present	2	102	98.1
	Overall Percentage				91.5

a. The cut value is .500

Variables in the Equation

		B	S.E.	Wald	df	Sig.	Exp(B)
Step 1[a]	Anoxic(1)	-18.241	13145.780	.000	1	.999	.000
	Phase2Num2(1)	-.592	1.341	.195	1	.659	.553
	StandardSoilNum			7.223	4	.125	
	StandardSoilNum(1)	3.113	1.984	2.461	1	.117	22.488
	StandardSoilNum(2)	20.911	6825.173	.000	1	.998	1206687848.545
	StandardSoilNum(3)	1.362	1.885	.522	1	.470	3.905
	StandardSoilNum(4)	-.586	1.448	.164	1	.686	.556
	State2Num(1)	-.142	1.220	.014	1	.907	.868
	BD(1)	.083	10821.066	.000	1	1.000	1.086
	AgeRange4Num(1)	-.078	1.373	.003	1	.955	.925
	Charnel(1)	.528	30831.241	.000	1	1.000	1.696
	SexNum(1)	-1.244	.995	1.563	1	.211	.288
	Constant	18.915	29914.039	.000	1	.999	163957108.335

a. Variable(s) entered on step 1: Anoxic, Phase2Num2, StandardSoilNum, State2Num, BD, AgeRange4Num, Charnel, SexNum.

11.4.2 Persistence of the Periosteal Surface Binary Logistic Regression Model 2

Case Processing Summary

Unweighted Cases[a]		N	Percent
Selected Cases	Included in Analysis	301	100.0
	Missing Cases	0	.0
	Total	301	100.0
Unselected Cases		0	.0
Total		301	100.0

a. If weight is in effect, see classification table for the total number of cases.

Omnibus Tests of Model Coefficients

		Chi-square	df	Sig.
Step 1	Step	55.128	13	.000
	Block	55.128	13	.000
	Model	55.128	13	.000

Model Summary

Step	-2 Log likelihood	Cox & Snell R Square	Nagelkerke R Square
1	148.791[a]	.167	.340

a. Estimation terminated at iteration number 20 because maximum iterations has been reached. Final solution cannot be found.

Hosmer and Lemeshow Test

Step	Chi-square	df	Sig.
1	5.207	8	.735

Contingency Table for Hosmer and Lemeshow Test

		Periosteal Surface = Absent		Periosteal Surface = Present		Total
		Observed	Expected	Observed	Expected	
Step 1	1	15	15.000	16	16.000	31
	2	5	4.471	21	21.529	26
	3	1	2.587	19	17.413	20
	4	4	3.299	27	27.701	31
	5	6	3.700	34	36.300	40
	6	0	2.082	28	25.918	28
	7	1	.861	29	29.139	30
	8	0	.000	29	29.000	29
	9	0	.000	19	19.000	19
	10	0	.000	47	47.000	47

Classification Table[a]

	Observed		Predicted		
			Periosteal Surface		Percentage Correct
			Absent	Present	
Step 1	Periosteal Surface	Absent	5	27	15.6
		Present	4	265	98.5
	Overall Percentage				89.7

a. The cut value is .500

Variables in the Equation

		B	S.E.	Wald	df	Sig.	Exp(B)
Step 1[a]	Anoxic(1)	-18.965	6319.464	.000	1	.998	.000
	Phase2Num2(1)	-.471	.782	.362	1	.547	.624
	StandardSoilNum			7.901	4	.095	
	StandardSoilNum(1)	20.579	20048.799	.000	1	.999	865964409.337
	StandardSoilNum(2)	39.483	21024.452	.000	1	.999	140380738810896064.000
	StandardSoilNum(3)	19.907	20048.799	.000	1	.999	442016010.481
	StandardSoilNum(4)	18.548	20048.799	.000	1	.999	113625235.888
	State2Num(1)	-.262	.643	.165	1	.684	.770
	Cave(1)	-21.268	20048.799	.000	1	.999	.000
	BD(1)	.082	10230.293	.000	1	1.000	1.085
	AgeRange4Num			.646	3	.886	
	AgeRange4Num(1)	-.251	.823	.093	1	.760	.778
	AgeRange4Num(2)	-.463	.793	.341	1	.559	.629
	AgeRange4Num(3)	.354	.721	.241	1	.624	1.424
	Charnel(1)	.084	.798	.011	1	.916	1.087
	Constant	22.118	12024.748	.000	1	.999	4031970548.826

a. Variable(s) entered on step 1: Anoxic, Phase2Num2, StandardSoilNum, State2Num, Cave, BD, AgeRange4Num, Charnel.

11.4.3 Persistence of the Periosteal Surface Binary Logistic Regression Model 3

Case Processing Summary

Unweighted Cases[a]		N	Percent
Selected Cases	Included in Analysis	301	100.0
	Missing Cases	0	.0
	Total	301	100.0
Unselected Cases		0	.0
Total		301	100.0

a. If weight is in effect, see classification table for the total number of cases.

Omnibus Tests of Model Coefficients

		Chi-square	df	Sig.
Step 1	Step	42.130	5	.000
	Block	42.130	5	.000
	Model	42.130	5	.000

Model Summary

Step	-2 Log likelihood	Cox & Snell R Square	Nagelkerke R Square
1	161.789[a]	.131	.265

a. Estimation terminated at iteration number 20 because maximum iterations has been reached. Final solution cannot be found.

Hosmer and Lemeshow Test

Step	Chi-square	df	Sig.
1	.272	4	.992

Contingency Table for Hosmer and Lemeshow Test

		Periosteal Surface = Absent		Periosteal Surface = Present		Total
		Observed	Expected	Observed	Expected	
Step 1	1	15	15.000	20	20.000	35
	2	4	4.000	20	20.000	24
	3	3	2.322	19	19.678	22
	4	9	9.678	128	127.322	137
	5	1	1.000	21	21.000	22
	6	0	.000	61	61.000	61

Classification Table[a]

	Observed		Predicted		
			Periosteal Surface		Percentage Correct
			Absent	Present	
Step 1	Periosteal Surface	Absent	0	32	.0
		Present	0	269	100.0
	Overall Percentage				89.4

a. The cut value is .500

Variables in the Equation

		B	S.E.	Wald	df	Sig.	Exp(B)
Step 1[a]	Phase2Num2(1)	-.440	.641	.472	1	.492	.644
	StandardSoilNum			11.042	4	.026	
	StandardSoilNum(1)	-.696	1.192	.341	1	.559	.498
	StandardSoilNum(2)	17.962	4981.059	.000	1	.997	63183658.614
	StandardSoilNum(3)	-1.391	1.187	1.373	1	.241	.249
	StandardSoilNum(4)	-2.546	1.084	5.512	1	.019	.078
	Constant	3.273	1.212	7.292	1	.007	26.392

a. Variable(s) entered on step 1: Phase2Num2, StandardSoilNum.

11.4.4 Persistence of the Periosteal Surface Binary Logistic Regression Model 4

Case Processing Summary

Unweighted Cases[a]		N	Percent
Selected Cases	Included in Analysis	301	100.0
	Missing Cases	0	.0
	Total	301	100.0
Unselected Cases		0	.0
Total		301	100.0

a. If weight is in effect, see classification table for the total number of cases.

Omnibus Tests of Model Coefficients

		Chi-square	df	Sig.
Step 1	Step	12.991	1	.000
	Block	12.991	1	.000
	Model	12.991	1	.000

Model Summary

Step	-2 Log likelihood	Cox & Snell R Square	Nagelkerke R Square
1	190.927[a]	.042	.086

a. Estimation terminated at iteration number 5 because parameter estimates changed by less than .001.

Hosmer and Lemeshow Test

Step	Chi-square	df	Sig.
1	.000	3	1.000

Contingency Table for Hosmer and Lemeshow Test

		Periosteal Surface = Absent		Periosteal Surface = Present		Total
		Observed	Expected	Observed	Expected	
Step 1	1	15	15.000	20	20.000	35
	2	4	4.000	20	20.000	24
	3	12	12.000	147	147.000	159
	4	1	1.000	17	17.000	18
	5	0	.000	65	65.000	65

Classification Table[a]

	Observed		Predicted		
			Periosteal Surface		Percentage Correct
			Absent	Present	
Step 1	Periosteal Surface	Absent	0	32	.0
		Present	0	269	100.0
	Overall Percentage				89.4

a. The cut value is .500

Variables in the Equation

		B	S.E.	Wald	df	Sig.	Exp(B)
Step 1[a]	StandardSoilNum	-.477	.130	13.406	1	.000	.621
	Constant	3.222	.392	67.384	1	.000	25.072

a. Variable(s) entered on step 1: StandardSoilNum.

11.5 ORANGE STAINING

11.5.1 Orange Staining Ordinal Regression Model 1

Case Processing Summary

		N	Marginal Percentage
Orange Staining	None	48	41.0%
	Superficial	38	32.5%
	Fair	28	23.9%
	Extensive	3	2.6%
Anoxic	Absent	106	90.6%
	Present	11	9.4%
Phase	Later Prehistoric	40	34.2%
	Historical	77	65.8%
Soil Type	Clay	30	25.6%
	Gravel	55	47.0%
	Sand	16	13.7%
	Silt	13	11.1%
	Open	3	2.6%
Cave	Non-Cave	114	97.4%
	Cave	3	2.6%
Black Death	Non-Black Death	95	81.2%
	Black Death	22	18.8%
State	Articulated	99	84.6%
	Disarticulated	18	15.4%
Charnel	Non-Charnel	115	98.3%
	Charnel	2	1.7%
Sex	Male	62	53.0%
	Female	55	47.0%
Age Range	Juvenile	12	10.3%
	Adult	105	89.7%
Valid		117	100.0%
Missing		184	
Total		301	

Model Fitting Information

Model	-2 Log Likelihood	Chi-Square	df	Sig.
Intercept Only	170.117			
Final	126.430	43.687	11	.000

Link function: Logit.

Goodness-of-Fit

	Chi-Square	df	Sig.
Pearson	94.535	91	.379
Deviance	85.674	91	.638

Link function: Logit.

Pseudo R-Square

Cox and Snell	.312
Nagelkerke	.345
McFadden	.160

Link function: Logit.

Parameter Estimates

		Estimate	Std. Error	Wald	df	Sig.	95% Confidence Interval	
							Lower Bound	Upper Bound
Threshold	[OrangeStain = 0]	.192	1.959	.010	1	.922	-3.648	4.032
	[OrangeStain = 1]	1.932	1.969	.963	1	.326	-1.927	5.791
	[OrangeStain = 2]	4.713	2.026	5.411	1	.020	.742	8.685
Location	[Anoxic=0]	.228	.758	.090	1	.764	-1.258	1.714
	[Anoxic=1]	0[a]	.	.	0	.	.	.
	[Phase2Num2=1]	-.331	.568	.339	1	.560	-1.443	.782
	[Phase2Num2=2]	0[a]	.	.	0	.	.	.
	[StandardSoilNum=1]	-.713	1.738	.168	1	.682	-4.120	2.694
	[StandardSoilNum=2]	-.502	1.744	.083	1	.773	-3.919	2.915
	[StandardSoilNum=3]	-1.883	1.763	1.140	1	.286	-5.339	1.573
	[StandardSoilNum=4]	-22.527	.000	.	1	.	-22.527	-22.527
	[StandardSoilNum=5]	0[a]	.	.	0	.	.	.
	[Cave=0]	0[a]	.	.	0	.	.	.
	[Cave=1]	0[a]	.	.	0	.	.	.
	[BD=0]	.734	.522	1.980	1	.159	-.289	1.757
	[BD=1]	0[a]	.	.	0	.	.	.
	[State2Num=1.00]	2.181	1.233	3.128	1	.077	-.236	4.598
	[State2Num=2.00]	0[a]	.	.	0	.	.	.
	[Charnel=0]	-1.244	1.502	.686	1	.408	-4.187	1.699
	[Charnel=1]	0[a]	.	.	0	.	.	.
	[SexNum=1]	.496	.391	1.610	1	.205	-.270	1.262
	[SexNum=2]	0[a]	.	.	0	.	.	.
	[AgeRange4Num=3.00]	-.197	.682	.083	1	.773	-1.534	1.140
	[AgeRange4Num=4.00]	0[a]	.	.	0	.	.	.

Link function: Logit.

a. This parameter is set to zero because it is redundant.

Test of Parallel Lines[a]

Model	-2 Log Likelihood	Chi-Square	df	Sig.
Null Hypothesis	126.430			
General	93.191[b]	33.238[c]	22	.059

The null hypothesis states that the location parameters (slope coefficients) are the same across response categories.

a. Link function: Logit.

b. The log-likelihood value cannot be further increased after maximum number of step-halving.

c. The Chi-Square statistic is computed based on the log-likelihood value of the last iteration of the general model. Validity of the test is uncertain.

11.5.2 Orange Staining Ordinal Regression Model 2

Case Processing Summary

		N	Marginal Percentage
Orange Staining	None	128	48.1%
	Superficial	86	32.3%
	Fair	46	17.3%
	Extensive	6	2.3%
Anoxic	Absent	240	90.2%
	Present	26	9.8%
Phase	Later Prehistoric	93	35.0%
	Historical	173	65.0%
Soil Type	Clay	124	46.6%
	Gravel	65	24.4%
	Sand	24	9.0%
	Silt	35	13.2%
	Open	18	6.8%
Cave	Non-Cave	244	91.7%
	Cave	22	8.3%
Black Death	Non-Black Death	241	90.6%
	Black Death	25	9.4%
State	Articulated	203	76.3%
	Disarticulated	63	23.7%
Charnel	Non-Charnel	213	80.1%
	Charnel	53	19.9%
Age Range	Neonate	29	10.9%
	Child	20	7.5%
	Juvenile	24	9.0%
	Adult	193	72.6%
Valid		266	100.0%
Missing		35	
Total		301	

Model Fitting Information

Model	-2 Log Likelihood	Chi-Square	df	Sig.
Intercept Only	280.166			
Final	209.940	70.226	13	.000

Link function: Logit.

Goodness-of-Fit

	Chi-Square	df	Sig.
Pearson	248.115	116	.000
Deviance	132.599	116	.139

Link function: Logit.

Pseudo R-Square

Cox and Snell	.232
Nagelkerke	.261
McFadden	.119

Link function: Logit.

Parameter Estimates

		Estimate	Std. Error	Wald	df	Sig.	95% Confidence Interval	
							Lower Bound	Upper Bound
Threshold	[OrangeStain = 0]	1.912	.928	4.244	1	.039	.093	3.731
	[OrangeStain = 1]	3.720	.949	15.352	1	.000	1.859	5.581
	[OrangeStain = 2]	6.186	1.033	35.868	1	.000	4.161	8.210
Location	[Anoxic=0]	-.911	.437	4.341	1	.037	-1.767	-.054
	[Anoxic=1]	0[a]	.	.	0	.	.	.
	[Phase2Num2=1]	-.269	.459	.344	1	.557	-1.168	.630
	[Phase2Num2=2]	0[a]	.	.	0	.	.	.
	[StandardSoilNum=1]	4.008	1.310	9.354	1	.002	1.440	6.577
	[StandardSoilNum=2]	4.796	1.338	12.851	1	.000	2.174	7.418
	[StandardSoilNum=3]	3.519	1.325	7.058	1	.008	.923	6.115
	[StandardSoilNum=4]	2.072	1.087	3.634	1	.057	-.058	4.201
	[StandardSoilNum=5]	0[a]	.	.	0	.	.	.
	[Cave=0]	-3.425	1.149	8.889	1	.003	-5.677	-1.174
	[Cave=1]	0[a]	.	.	0	.	.	.
	[BD=0]	.684	.482	2.012	1	.156	-.261	1.628
	[BD=1]	0[a]	.	.	0	.	.	.
	[State2Num=1.00]	.992	.582	2.907	1	.088	-.148	2.133
	[State2Num=2.00]	0[a]	.	.	0	.	.	.
	[Charnel=0]	1.235	.425	8.446	1	.004	.402	2.068
	[Charnel=1]	0[a]	.	.	0	.	.	.
	[AgeRange4Num=1.00]	.131	.451	.084	1	.771	-.752	1.014
	[AgeRange4Num=2.00]	-.195	.484	.162	1	.687	-1.144	.754
	[AgeRange4Num=3.00]	-.184	.465	.157	1	.692	-1.095	.727
	[AgeRange4Num=4.00]	0[a]	.	.	0	.	.	.

Link function: Logit.

a. This parameter is set to zero because it is redundant.

Test of Parallel Lines[a]

Model	-2 Log Likelihood	Chi-Square	df	Sig.
Null Hypothesis	209.940			
General	.000[b]	209.940	26	.000

The null hypothesis states that the location parameters (slope coefficients) are the same across response categories.

a. Link function: Logit.

b. The log-likelihood value is practically zero. There may be a complete separation in the data. The maximum likelihood estimates do not exist.

11.5.3 Orange Staining Ordinal Regression Model 3

Case Processing Summary

		N	Marginal Percentage
Orange Staining	None	128	48.1%
	Superficial	86	32.3%
	Fair	46	17.3%
	Extensive	6	2.3%
Anoxic	Absent	240	90.2%
	Present	26	9.8%
Soil Type	Clay	124	46.6%
	Gravel	65	24.4%
	Sand	24	9.0%
	Silt	35	13.2%
Cave	Open	18	6.8%
	Non-Cave	244	91.7%
	Cave	22	8.3%
State	Articulated	203	76.3%
	Disarticulated	63	23.7%
Charnel	Non-Charnel	213	80.1%
	Charnel	53	19.9%
Valid		266	100.0%
Missing		35	
Total		301	

Model Fitting Information

Model	-2 Log Likelihood	Chi-Square	df	Sig.
Intercept Only	165.300			
Final	97.676	67.624	8	.000

Link function: Logit.

Goodness-of-Fit

	Chi-Square	df	Sig.
Pearson	65.825	31	.000
Deviance	35.692	31	.257

Link function: Logit.

Pseudo R-Square

Cox and Snell	.224
Nagelkerke	.252
McFadden	.115

Link function: Logit.

Parameter Estimates

		Estimate	Std. Error	Wald	df	Sig.	95% Confidence Interval	
							Lower Bound	Upper Bound
Threshold	[OrangeStain = 0]	1.497	.732	4.184	1	.041	.063	2.931
	[OrangeStain = 1]	3.288	.753	19.084	1	.000	1.813	4.763
	[OrangeStain = 2]	5.748	.849	45.888	1	.000	4.085	7.411
Location	[Anoxic=0]	-.884	.431	4.214	1	.040	-1.728	-.040
	[Anoxic=1]	0[a]	.	.	0	.	.	.
	[StandardSoilNum=1]	4.121	1.282	10.341	1	.001	1.609	6.633
	[StandardSoilNum=2]	4.644	1.293	12.888	1	.000	2.108	7.179
	[StandardSoilNum=3]	3.577	1.312	7.433	1	.006	1.005	6.148
	[StandardSoilNum=4]	2.037	1.076	3.586	1	.058	-.071	4.146
	[StandardSoilNum=5]	0[a]	.	.	0	.	.	.
	[Cave=0]	-3.515	1.136	9.580	1	.002	-5.741	-1.289
	[Cave=1]	0[a]	.	.	0	.	.	.
	[State2Num=1.00]	1.195	.510	5.491	1	.019	.195	2.195
	[State2Num=2.00]	0[a]	.	.	0	.	.	.
	[Charnel=0]	1.212	.373	10.559	1	.001	.481	1.943
	[Charnel=1]	0[a]	.	.	0	.	.	.

Link function: Logit.

a. This parameter is set to zero because it is redundant.

Test of Parallel Lines[a]

Model	-2 Log Likelihood	Chi-Square	df	Sig.
Null Hypothesis	97.676			
General	.000[b]	97.676	16	.000

The null hypothesis states that the location parameters (slope coefficients) are the same across response categories.

a. Link function: Logit.

b. The log-likelihood value is practically zero. There may be a complete separation in the data. The maximum likelihood estimates do not exist.

11.5.4 Orange Staining Ordinal Regression Model 4

Case Processing Summary

		N	Marginal Percentage
Orange Staining	None	128	48.1%
	Superficial	86	32.3%
	Fair	46	17.3%
	Extensive	6	2.3%
Soil Type	Clay	124	46.6%
	Gravel	65	24.4%
	Sand	24	9.0%
	Silt	35	13.2%
	Open	18	6.8%
Charnel	Non-Charnel	213	80.1%
	Charnel	53	19.9%
Valid		266	100.0%
Missing		35	
Total		301	

Model Fitting Information

Model	-2 Log Likelihood	Chi-Square	df	Sig.
Intercept Only	113.835			
Final	64.364	49.470	5	.000

Link function: Logit.

Goodness-of-Fit

	Chi-Square	df	Sig.
Pearson	17.878	10	.057
Deviance	15.295	10	.122

Link function: Logit.

Pseudo R-Square

Cox and Snell	.170
Nagelkerke	.191
McFadden	.084

Link function: Logit.

Parameter Estimates

		Estimate	Std. Error	Wald	df	Sig.	95% Confidence Interval	
							Lower Bound	Upper Bound
Threshold	[OrangeStain = 0]	2.074	.652	10.105	1	.001	.795	3.352
	[OrangeStain = 1]	3.789	.681	30.997	1	.000	2.455	5.123
	[OrangeStain = 2]	6.232	.788	62.536	1	.000	4.687	7.776
Location	[StandardSoilNum=1]	1.769	.596	8.803	1	.003	.600	2.937
	[StandardSoilNum=2]	2.269	.603	14.158	1	.000	1.087	3.451
	[StandardSoilNum=3]	.877	.682	1.657	1	.198	-.459	2.213
	[StandardSoilNum=4]	-.370	.707	.274	1	.601	-1.756	1.016
	[StandardSoilNum=5]	0[a]	.	.	0	.	.	.
	[Charnel=0]	.900	.350	6.629	1	.010	.215	1.586
	[Charnel=1]	0[a]	.	.	0	.	.	.

Link function: Logit.

a. This parameter is set to zero because it is redundant.

Test of Parallel Lines[a]

Model	-2 Log Likelihood	Chi-Square	df	Sig.
Null Hypothesis	64.364			
General	.000[b]	64.364	10	.000

The null hypothesis states that the location parameters (slope coefficients) are the same across response categories.

a. Link function: Logit.

b. The log-likelihood value is practically zero. There may be a complete separation in the data. The maximum likelihood estimates do not exist.

11.5.5 Orange Staining Ordinal Regression Model 5

Case Processing Summary

		N	Marginal Percentage
Orange Staining	None	128	48.1%
	Superficial	86	32.3%
	Fair	46	17.3%
	Extensive	6	2.3%
Soil Type	Clay	124	46.6%
	Gravel	65	24.4%
	Sand	24	9.0%
	Silt	35	13.2%
	Open	18	6.8%
Valid		266	100.0%
Missing		35	
Total		301	

Model Fitting Information

Model	-2 Log Likelihood	Chi-Square	df	Sig.
Intercept Only	96.918			
Final	54.215	42.703	4	.000

Link function: Logit.

Goodness-of-Fit

	Chi-Square	df	Sig.
Pearson	15.153	8	.056
Deviance	13.035	8	.111

Link function: Logit.

Pseudo R-Square

Cox and Snell	.148
Nagelkerke	.167
McFadden	.073

Link function: Logit.

Parameter Estimates

		Estimate	Std. Error	Wald	df	Sig.	95% Confidence Interval	
							Lower Bound	Upper Bound
Threshold	[OrangeStain = 0]	1.176	.552	4.543	1	.033	.095	2.258
	[OrangeStain = 1]	2.852	.572	24.835	1	.000	1.731	3.974
	[OrangeStain = 2]	5.278	.694	57.907	1	.000	3.919	6.637
Location	[StandardSoilNum=1]	1.376	.578	5.665	1	.017	.243	2.508
	[StandardSoilNum=2]	2.248	.603	13.899	1	.000	1.066	3.429
	[StandardSoilNum=3]	.874	.682	1.642	1	.200	-.463	2.210
	[StandardSoilNum=4]	-.369	.707	.272	1	.602	-1.755	1.018
	[StandardSoilNum=5]	0[a]	.	.	0	.	.	.

Link function: Logit.

a. This parameter is set to zero because it is redundant.

Test of Parallel Lines[a]

Model	-2 Log Likelihood	Chi-Square	df	Sig.
Null Hypothesis	54.215			
General	.000[b]	54.215	8	.000

The null hypothesis states that the location parameters (slope coefficients) are the same across response categories.

a. Link function: Logit.

b. The log-likelihood value is practically zero. There may be a complete separation in the data. The maximum likelihood estimates do not exist.

11.6 BROWN STAINING

11.6.1 Brown Staining Ordinal Regression Model 1

Case Processing Summary

		N	Marginal Percentage
Brown Staining	None	105	89.7%
	Superifical	6	5.1%
	Fair	6	5.1%
Anoxic	Absent	106	90.6%
	Present	11	9.4%
Phase	Later Prehistoric	40	34.2%
	Historical	77	65.8%
Soil Type	Clay	30	25.6%
	Gravel	55	47.0%
	Sand	16	13.7%
	Silt	13	11.1%
	Open	3	2.6%
Cave	Non-Cave	114	97.4%
	Cave	3	2.6%
State	Articulated	99	84.6%
	Disarticulated	18	15.4%
Charnel	Non-Charnel	115	98.3%
	Charnel	2	1.7%
Sex	Male	62	53.0%
	Female	55	47.0%
Age Range	Juvenile	12	10.3%
	Adult	105	89.7%
Black Death	Non-Black Death	95	81.2%
	Black Death	22	18.8%
Valid		117	100.0%
Missing		184	
Total		301	

Model Fitting Information

Model	-2 Log Likelihood	Chi-Square	df	Sig.
Intercept Only	68.425			
Final	54.226	14.199	11	.222

Link function: Logit.

Goodness-of-Fit

	Chi-Square	df	Sig.
Pearson	53.185	57	.619
Deviance	41.683	57	.936

Link function: Logit.

Pseudo R-Square

Cox and Snell	.114
Nagelkerke	.207
McFadden	.151

Link function: Logit.

Parameter Estimates

		Estimate	Std. Error	Wald	df	Sig.	95% Confidence Interval	
							Lower Bound	Upper Bound
Threshold	[BrownStain = 0]	32.343	3358.687	.000	1	.992	-6550.562	6615.248
	[BrownStain = 1]	33.202	3358.687	.000	1	.992	-6549.703	6616.107
Location	[Anoxic=0]	-.626	1.499	.175	1	.676	-3.564	2.311
	[Anoxic=1]	0[a]	.	.	0	.	.	.
	[Phase2Num2=1]	2.463	.918	7.203	1	.007	.664	4.262
	[Phase2Num2=2]	0[a]	.	.	0	.	.	.
	[StandardSoilNum=1]	15.161	3358.686	.000	1	.996	-6567.744	6598.065
	[StandardSoilNum=2]	16.891	3358.686	.000	1	.996	-6566.013	6599.795
	[StandardSoilNum=3]	17.654	3358.686	.000	1	.996	-6565.250	6600.558
	[StandardSoilNum=4]	14.912	3358.686	.000	1	.996	-6567.992	6597.817
	[StandardSoilNum=5]	0[a]	.	.	0	.	.	.
	[Cave=0]	0[a]	.	.	0	.	.	.
	[Cave=1]	0[a]	.	.	0	.	.	.
	[State2Num=1.00]	.455	1.129	.163	1	.687	-1.757	2.667
	[State2Num=2.00]	0[a]	.	.	0	.	.	.
	[Charnel=0]	13.513	.000	.	1	.	13.513	13.513
	[Charnel=1]	0[a]	.	.	0	.	.	.
	[SexNum=1]	-.523	.670	.610	1	.435	-1.836	.789
	[SexNum=2]	0[a]	.	.	0	.	.	.
	[AgeRange4Num=3.00]	-.440	1.209	.133	1	.716	-2.810	1.929
	[AgeRange4Num=4.00]	0[a]	.	.	0	.	.	.
	[BD=0]	-.344	1.032	.111	1	.739	-2.367	1.680
	[BD=1]	0[a]	.	.	0	.	.	.

Link function: Logit.

a. This parameter is set to zero because it is redundant.

Test of Parallel Lines[a]

Model	-2 Log Likelihood	Chi-Square	df	Sig.
Null Hypothesis	54.226			
General	48.231[b]	5.995[c]	11	.874

The null hypothesis states that the location parameters (slope coefficients) are the same across response categories.

a. Link function: Logit.

b. The log-likelihood value cannot be further increased after maximum number of step-halving.

c. The Chi-Square statistic is computed based on the log-likelihood value of the last iteration of the general model. Validity of the test is uncertain.

11.6.2 Brown Staining Ordinal Regression Model 2

Case Processing Summary

		N	Marginal Percentage
Brown Staining	None	243	91.4%
	Superifical	15	5.6%
	Fair	7	2.6%
	Extensive	1	0.4%
Anoxic	Absent	240	90.2%
	Present	26	9.8%
Phase	Later Prehistoric	93	35.0%
	Historical	173	65.0%
Soil Type	Clay	124	46.6%
	Gravel	65	24.4%
	Sand	24	9.0%
	Silt	35	13.2%
	Open	18	6.8%
Cave	Non-Cave	244	91.7%
	Cave	22	8.3%
State	Articulated	203	76.3%
	Disarticulated	63	23.7%
Charnel	Non-Charnel	213	80.1%
	Charnel	53	19.9%
Age Range	Neonate	29	10.9%
	Child	20	7.5%
	Juvenile	24	9.0%
	Adult	193	72.6%
Black Death	Non-Black Death	241	90.6%
	Black Death	25	9.4%
Valid		266	100.0%
Missing		35	
Total		301	

Model Fitting Information

Model	-2 Log Likelihood	Chi-Square	df	Sig.
Intercept Only	106.668			
Final	85.072	21.595	13	.062

Link function: Logit.

Goodness-of-Fit

	Chi-Square	df	Sig.
Pearson	77.594	116	.998
Deviance	57.862	116	1.000

Link function: Logit.

Pseudo R-Square

Cox and Snell	.078
Nagelkerke	.152
McFadden	.112

Link function: Logit.

Parameter Estimates

		Estimate	Std. Error	Wald	df	Sig.	95% Confidence Interval	
							Lower Bound	Upper Bound
Threshold	[BrownStain = 0]	17.462	1469.435	.000	1	.991	-2862.578	2897.503
	[BrownStain = 1]	18.644	1469.435	.000	1	.990	-2861.396	2898.684
	[BrownStain = 2]	20.818	1469.436	.000	1	.989	-2859.223	2900.859
Location	[Anoxic=0]	-.134	.745	.032	1	.858	-1.594	1.327
	[Anoxic=1]	0[a]	.	.	0	.	.	.
	[Phase2Num2=1]	2.153	.773	7.758	1	.005	.638	3.667
	[Phase2Num2=2]	0[a]	.	.	0	.	.	.
	[StandardSoilNum=1]	.701	1469.435	.000	1	1.000	-2879.338	2880.741
	[StandardSoilNum=2]	1.891	1469.435	.000	1	.999	-2878.149	2881.931
	[StandardSoilNum=3]	2.245	1469.435	.000	1	.999	-2877.794	2882.285
	[StandardSoilNum=4]	.258	1469.435	.000	1	1.000	-2879.782	2880.297
	[StandardSoilNum=5]	0[a]	.	.	0	.	.	.
	[Cave=0]	14.478	.000	.	1	.	14.478	14.478
	[Cave=1]	0[a]	.	.	0	.	.	.
	[State2Num=1.00]	.661	.755	.768	1	.381	-.818	2.140
	[State2Num=2.00]	0[a]	.	.	0	.	.	.
	[Charnel=0]	-1.909	.898	4.519	1	.034	-3.669	-.149
	[Charnel=1]	0[a]	.	.	0	.	.	.
	[AgeRange4Num=1.00]	.667	.948	.495	1	.482	-1.191	2.524
	[AgeRange4Num=2.00]	-14.563	1162.260	.000	1	.990	-2292.550	2263.424
	[AgeRange4Num=3.00]	.104	.696	.022	1	.882	-1.260	1.467
	[AgeRange4Num=4.00]	0[a]	.	.	0	.	.	.
	[BD=0]	-.229	.990	.054	1	.817	-2.169	1.711
	[BD=1]	0[a]	.	.	0	.	.	.

Link function: Logit.

a. This parameter is set to zero because it is redundant.

Test of Parallel Lines[a]

Model	-2 Log Likelihood	Chi-Square	df	Sig.
Null Hypothesis	85.072			
General	30.688[b]	54.384[c]	26	.001

The null hypothesis states that the location parameters (slope coefficients) are the same across response categories.

a. Link function: Logit.

b. The log-likelihood value cannot be further increased after maximum number of step-halving.

c. The Chi-Square statistic is computed based on the log-likelihood value of the last iteration of the general model. Validity of the test is uncertain.

11.6.3 Brown Staining Ordinal Regression Model 3

Case Processing Summary

		N	Marginal Percentage
Brown Staining	None	243	91.4%
	Superifical	15	5.6%
	Fair	7	2.6%
	Extensive	1	0.4%
Phase	Later Prehistoric	93	35.0%
	Historical	173	65.0%
Charnel	Non-Charnel	213	80.1%
	Charnel	53	19.9%
Valid		266	100.0%
Missing		35	
Total		301	

Model Fitting Information

Model	-2 Log Likelihood	Chi-Square	df	Sig.
Intercept Only	30.854			
Final	27.015	3.839	2	.147

Link function: Logit.

Goodness-of-Fit

	Chi-Square	df	Sig.
Pearson	6.707	4	.152
Deviance	8.783	4	.067

Link function: Logit.

Pseudo R-Square

Cox and Snell	.014
Nagelkerke	.028
McFadden	.020

Link function: Logit.

Parameter Estimates

		Estimate	Std. Error	Wald	df	Sig.	95% Confidence Interval	
							Lower Bound	Upper Bound
Threshold	[BrownStain = 0]	1.935	.413	21.951	1	.000	1.126	2.745
	[BrownStain = 1]	3.060	.500	37.454	1	.000	2.080	4.041
	[BrownStain = 2]	5.167	1.060	23.771	1	.000	3.090	7.244
Location	[Phase2Num2=1]	.840	.533	2.485	1	.115	-.204	1.885
	[Phase2Num2=2]	0[a]	.	.	0	.	.	.
	[Charnel=0]	-1.002	.587	2.911	1	.088	-2.152	.149
	[Charnel=1]	0[a]	.	.	0	.	.	.

Link function: Logit.

a. This parameter is set to zero because it is redundant.

Test of Parallel Lines[a]

Model	-2 Log Likelihood	Chi-Square	df	Sig.
Null Hypothesis	27.015			
General	18.232	8.783	4	.067

The null hypothesis states that the location parameters (slope coefficients) are the same across response categories.

a. Link function: Logit.

11.7 YELLOW STAINING

11.7.1 Yellow Staining Ordinal Regression Model 1

Case Processing Summary

		N	Marginal Percentage
Yellow Staining	None	110	94.0%
	Superifical	5	4.3%
	Fair	2	1.7%
Anoxic	Absent	106	90.6%
	Present	11	9.4%
Phase	Later Prehistoric	40	34.2%
	Historical	77	65.8%
Soil Type	Clay	30	25.6%
	Gravel	55	47.0%
	Sand	16	13.7%
	Silt	13	11.1%
	Open	3	2.6%
Cave	Non-Cave	114	97.4%
	Cave	3	2.6%
Black Death	Non-Black Death	95	81.2%
	Black Death	22	18.8%
State	Articulated	99	84.6%
	Disarticulated	18	15.4%
Charnel	Non-Charnel	115	98.3%
	Charnel	2	1.7%
Sex	Male	62	53.0%
	Female	55	47.0%
Age Range	Juvenile	12	10.3%
	Adult	105	89.7%
Valid		117	100.0%
Missing		184	
Total		301	

Model Fitting Information

Model	-2 Log Likelihood	Chi-Square	df	Sig.
Intercept Only	40.778			
Final	24.938	15.840	11	.147

Link function: Logit.

Goodness-of-Fit

	Chi-Square	df	Sig.
Pearson	23.582	57	1.000
Deviance	16.918	57	1.000

Link function: Logit.

Pseudo R-Square

Cox and Snell	.127
Nagelkerke	.310
McFadden	.258

Link function: Logit.

Parameter Estimates

		Estimate	Std. Error	Wald	df	Sig.	95% Confidence Interval	
							Lower Bound	Upper Bound
Threshold	[YelloStain = 0]	-1.717	15719.166	.000	1	1.000	-30810.716	30807.282
	[YelloStain = 1]	-.290	15719.166	.000	1	1.000	-30809.289	30808.709
Location	[Anoxic=0]	-1.863	1.617	1.327	1	.249	-5.033	1.307
	[Anoxic=1]	0[a]	.	.	0	.	.	.
	[Phase2Num2=1]	.869	1.594	.297	1	.585	-2.255	3.994
	[Phase2Num2=2]	0[a]	.	.	0	.	.	.
	[StandardSoilNum=1]	1.337	15100.039	.000	1	1.000	-29594.196	29596.869
	[StandardSoilNum=2]	-14.455	15719.166	.000	1	.999	-30823.453	30794.544
	[StandardSoilNum=3]	2.603	15100.039	.000	1	1.000	-29592.930	29598.135
	[StandardSoilNum=4]	-14.049	16370.423	.000	1	.999	-32099.488	32071.390
	[StandardSoilNum=5]	0[a]	.	.	0	.	.	.
	[Cave=0]	0[a]	.	.	0	.	.	.
	[Cave=1]	0[a]	.	.	0	.	.	.
	[BD=0]	-18.825	4368.181	.000	1	.997	-8580.302	8542.653
	[BD=1]	0[a]	.	.	0	.	.	.
	[State2Num=1.00]	15.332	.000	.	1	.	15.332	15.332
	[State2Num=2.00]	0[a]	.	.	0	.	.	.
	[Charnel=0]	-2.242	1.990	1.269	1	.260	-6.143	1.658
	[Charnel=1]	0[a]	.	.	0	.	.	.
	[SexNum=1]	.221	.903	.060	1	.806	-1.549	1.992
	[SexNum=2]	0[a]	.	.	0	.	.	.
	[AgeRange4Num=3.00]	-16.447	6080.819	.000	1	.998	-11934.633	11901.740
	[AgeRange4Num=4.00]	0[a]	.	.	0	.	.	.

Link function: Logit.

a. This parameter is set to zero because it is redundant.

Test of Parallel Lines[a]

Model	-2 Log Likelihood	Chi-Square	df	Sig.
Null Hypothesis	24.938			
General	.000[b]	24.938	11	.009

The null hypothesis states that the location parameters (slope coefficients) are the same across response categories.

a. Link function: Logit.

b. The log-likelihood value is practically zero. There may be a complete separation in the data. The maximum likelihood estimates do not exist.

11.7.2 Yellow Staining Ordinal Regression Model 2

Case Processing Summary

		N	Marginal Percentage
Yellow Staining	None	251	94.4%
	Superifical	12	4.5%
	Fair	2	0.8%
	Extensive	1	0.4%
Anoxic	Absent	240	90.2%
	Present	26	9.8%
Phase	Later Prehistoric	93	35.0%
	Historical	173	65.0%
Soil Type	Clay	124	46.6%
	Gravel	65	24.4%
	Sand	24	9.0%
	Silt	35	13.2%
Cave	Open	18	6.8%
	Non-Cave	244	91.7%
	Cave	22	8.3%
Black Death	Non-Black Death	241	90.6%
	Black Death	25	9.4%
State	Articulated	203	76.3%
	Disarticulated	63	23.7%
Charnel	Non-Charnel	213	80.1%
	Charnel	53	19.9%
Age Range	Neonate	29	10.9%
	Child	20	7.5%
	Juvenile	24	9.0%
	Adult	193	72.6%
Valid		266	100.0%
Missing		35	
Total		301	

Model Fitting Information

Model	-2 Log Likelihood	Chi-Square	df	Sig.
Intercept Only	69.011			
Final	54.411	14.600	13	.333

Link function: Logit.

Goodness-of-Fit

	Chi-Square	df	Sig.
Pearson	53.871	116	1.000
Deviance	31.210	116	1.000

Link function: Logit.

Pseudo R-Square

Cox and Snell	.053
Nagelkerke	.135
McFadden	.109

Link function: Logit.

Parameter Estimates

		Estimate	Std. Error	Wald	df	Sig.	95% Confidence Interval	
							Lower Bound	Upper Bound
Threshold	[YelloStain = 0]	-14.658	1182.557	.000	1	.990	-2332.428	2303.112
	[YelloStain = 1]	-12.948	1182.558	.000	1	.991	-2330.719	2304.822
	[YelloStain = 2]	-11.832	1182.558	.000	1	.992	-2329.603	2305.938
Location	[Anoxic=0]	-.391	.919	.181	1	.670	-2.192	1.409
	[Anoxic=1]	0[a]	.	.	0	.	.	.
	[Phase2Num2=1]	.052	1.316	.002	1	.968	-2.527	2.632
	[Phase2Num2=2]	0[a]	.	.	0	.	.	.
	[StandardSoilNum=1]	-14.275	1.484	92.528	1	.000	-17.184	-11.367
	[StandardSoilNum=2]	-28.403	1182.557	.001	1	.981	-2346.172	2289.366
	[StandardSoilNum=3]	-13.016	1.358	91.798	1	.000	-15.678	-10.353
	[StandardSoilNum=4]	-14.675	1.458	101.347	1	.000	-17.532	-11.818
	[StandardSoilNum=5]	0[a]	.	.	0	.	.	.
	[Cave=0]	14.369	.000	.	1	.	14.369	14.369
	[Cave=1]	0[a]	.	.	0	.	.	.
	[BD=0]	-16.168	1182.556	.000	1	.989	-2333.935	2301.599
	[BD=1]	0[a]	.	.	0	.	.	.
	[State2Num=1.00]	-.835	1.268	.434	1	.510	-3.320	1.649
	[State2Num=2.00]	0[a]	.	.	0	.	.	.
	[Charnel=0]	-1.014	1.101	.848	1	.357	-3.172	1.145
	[Charnel=1]	0[a]	.	.	0	.	.	.
	[AgeRange4Num=1.00]	.058	1.214	.002	1	.962	-2.321	2.436
	[AgeRange4Num=2.00]	-14.197	1455.002	.000	1	.992	-2865.948	2837.555
	[AgeRange4Num=3.00]	.191	.895	.046	1	.831	-1.563	1.945
	[AgeRange4Num=4.00]	0[a]	.	.	0	.	.	.

Link function: Logit.

a. This parameter is set to zero because it is redundant.

Test of Parallel Lines[a]

Model	-2 Log Likelihood	Chi-Square	df	Sig.
Null Hypothesis	54.411			
General	.000[b]	54.411	26	.001

The null hypothesis states that the location parameters (slope coefficients) are the same across response categories.

a. Link function: Logit.

b. The log-likelihood value is practically zero. There may be a complete separation in the data. The maximum likelihood estimates do not exist.

11.7.3 Yellow Staining Ordinal Regression Model 3

Case Processing Summary

		N	Marginal Percentage
Yellow Staining	None	251	94.4%
	Superifical	12	4.5%
	Fair	2	0.8%
	Extensive	1	0.4%
Soil Type	Clay	124	46.6%
	Gravel	65	24.4%
	Sand	24	9.0%
	Silt	35	13.2%
	Open	18	6.8%
Valid		266	100.0%
Missing		35	
Total		301	

Model Fitting Information

Model	-2 Log Likelihood	Chi-Square	df	Sig.
Intercept Only	31.241			
Final	28.942	2.300	4	.681

Link function: Logit.

Goodness-of-Fit

	Chi-Square	df	Sig.
Pearson	21.420	8	.006
Deviance	13.396	8	.099

Link function: Logit.

Pseudo R-Square

Cox and Snell	.009
Nagelkerke	.022
McFadden	.017

Link function: Logit.

Parameter Estimates

		Estimate	Std. Error	Wald	df	Sig.	95% Confidence Interval	
							Lower Bound	Upper Bound
Threshold	[YelloStain = 0]	2.845	1.034	7.569	1	.006	.818	4.871
	[YelloStain = 1]	4.511	1.157	15.202	1	.000	2.243	6.779
	[YelloStain = 2]	5.616	1.417	15.721	1	.000	2.840	8.393
Location	[StandardSoilNum=1]	-.144	1.116	.017	1	.897	-2.332	2.044
	[StandardSoilNum=2]	.138	1.154	.014	1	.905	-2.124	2.399
	[StandardSoilNum=3]	.869	1.207	.518	1	.471	-1.497	3.236
	[StandardSoilNum=4]	-.654	1.439	.206	1	.650	-3.475	2.167
	[StandardSoilNum=5]	0[a]	.	.	0	.	.	.

Link function: Logit.

a. This parameter is set to zero because it is redundant.

Test of Parallel Lines[a]

Model	-2 Log Likelihood	Chi-Square	df	Sig.
Null Hypothesis	28.942			
General	.000[b]	28.942	8	.000

The null hypothesis states that the location parameters (slope coefficients) are the same across response categories.
a. Link function: Logit.
b. The log-likelihood value is practically zero. There may be a complete separation in the data. The maximum likelihood estimates do not exist.

11.8 ORANGE INCLUSIONS

11.8.1 Orange Inclusions Ordinal Regression Model 1

Case Processing Summary

		N	Marginal Percentage
Orange Inclusions	None	20	17.1%
	Infrequent	50	42.7%
	Frequent	46	39.3%
	Pervasive	1	0.9%
Anoxic	Absent	106	90.6%
	Present	11	9.4%
Phase	Later Prehistoric	40	34.2%
	Historical	77	65.8%
Soil Type	Clay	30	25.6%
	Gravel	55	47.0%
	Sand	16	13.7%
	Silt	13	11.1%
Cave	Open	3	2.6%
	Non-Cave	114	97.4%
	Cave	3	2.6%
Black Death	Non-Black Death	95	81.2%
	Black Death	22	18.8%
State	Articulated	99	84.6%
	Disarticulated	18	15.4%
Charnel	Non-Charnel	115	98.3%
	Charnel	2	1.7%
Sex	Male	62	53.0%
	Female	55	47.0%
Age Range	Juvenile	12	10.3%
	Adult	105	89.7%
Valid		117	100.0%
Missing		184	
Total		301	

Model Fitting Information

Model	-2 Log Likelihood	Chi-Square	df	Sig.
Intercept Only	150.909			
Final	106.964	43.946	11	.000

Link function: Logit.

Goodness-of-Fit

	Chi-Square	df	Sig.
Pearson	135.404	91	.002
Deviance	66.968	91	.972

Link function: Logit.

Pseudo R-Square

Cox and Snell	.313
Nagelkerke	.355
McFadden	.175

Link function: Logit.

Parameter Estimates

		Estimate	Std. Error	Wald	df	Sig.	95% Confidence Interval	
							Lower Bound	Upper Bound
Threshold	[OrangeInc = 0]	-4.276	2.377	3.236	1	.072	-8.934	.383
	[OrangeInc = 1]	-1.621	2.362	.471	1	.492	-6.250	3.007
	[OrangeInc = 2]	3.118	2.368	1.734	1	.188	-1.523	7.759
Location	[Anoxic=0]	-.464	.813	.325	1	.568	-2.057	1.129
	[Anoxic=1]	0[a]	.	.	0	.	.	.
	[Phase2Num2=1]	.419	.580	.522	1	.470	-.718	1.557
	[Phase2Num2=2]	0[a]	.	.	0	.	.	.
	[StandardSoilNum=1]	1.032	1.420	.529	1	.467	-1.750	3.815
	[StandardSoilNum=2]	-.002	1.437	.000	1	.999	-2.819	2.815
	[StandardSoilNum=3]	.820	1.416	.336	1	.562	-1.955	3.595
	[StandardSoilNum=4]	-3.308	1.437	5.296	1	.021	-6.125	-.491
	[StandardSoilNum=5]	0[a]	.	.	0	.	.	.
	[Cave=0]	0[a]	.	.	0	.	.	.
	[Cave=1]	0[a]	.	.	0	.	.	.
	[BD=0]	-1.010	.550	3.367	1	.066	-2.088	.069
	[BD=1]	0[a]	.	.	0	.	.	.
	[State2Num=1.00]	.737	.828	.794	1	.373	-.885	2.360
	[State2Num=2.00]	0[a]	.	.	0	.	.	.
	[Charnel=0]	-1.898	2.058	.851	1	.356	-5.932	2.135
	[Charnel=1]	0[a]	.	.	0	.	.	.
	[SexNum=1]	-.023	.387	.004	1	.952	-.782	.735
	[SexNum=2]	0[a]	.	.	0	.	.	.
	[AgeRange4Num=3.00]	.545	.656	.689	1	.406	-.741	1.831
	[AgeRange4Num=4.00]	0[a]	.	.	0	.	.	.

Link function: Logit.

a. This parameter is set to zero because it is redundant.

Test of Parallel Lines[a]

Model	-2 Log Likelihood	Chi-Square	df	Sig.
Null Hypothesis	106.964			
General	.000[b]	106.964	22	.000

The null hypothesis states that the location parameters (slope coefficients) are the same across response categories.

a. Link function: Logit.

b. The log-likelihood value is practically zero. There may be a complete separation in the data. The maximum likelihood estimates do not exist.

11.8.2 Orange Inclusions Ordinal Regression Model 2

Case Processing Summary

		N	Marginal Percentage
Orange Inclusions	None	46	17.3%
	Infrequent	124	46.6%
	Frequent	93	35.0%
	Pervasive	3	1.1%
Anoxic	Absent	240	90.2%
	Present	26	9.8%
Phase	Later Prehistoric	93	35.0%
	Historical	173	65.0%
Soil Type	Clay	124	46.6%
	Gravel	65	24.4%
	Sand	24	9.0%
	Silt	35	13.2%
Cave	Open	18	6.8%
	Non-Cave	244	91.7%
	Cave	22	8.3%
Black Death	Non-Black Death	241	90.6%
	Black Death	25	9.4%
State	Articulated	203	76.3%
	Disarticulated	63	23.7%
Charnel	Non-Charnel	213	80.1%
	Charnel	53	19.9%
Age Range	Neonate	29	10.9%
	Child	20	7.5%
	Juvenile	24	9.0%
	Adult	193	72.6%
Valid		266	100.0%
Missing		35	
Total		301	

Model Fitting Information

Model	-2 Log Likelihood	Chi-Square	df	Sig.
Intercept Only	249.783			
Final	192.184	57.598	13	.000

Link function: Logit.

Goodness-of-Fit

	Chi-Square	df	Sig.
Pearson	175.125	116	.000
Deviance	117.545	116	.442

Link function: Logit.

Pseudo R-Square

Cox and Snell	.195
Nagelkerke	.220
McFadden	.101

Link function: Logit.

Parameter Estimates

		Estimate	Std. Error	Wald	df	Sig.	95% Confidence Interval	
							Lower Bound	Upper Bound
Threshold	[OrangeInc = 0]	-.768	.895	.736	1	.391	-2.522	.986
	[OrangeInc = 1]	1.759	.899	3.826	1	.050	-.003	3.522
	[OrangeInc = 2]	5.917	1.079	30.059	1	.000	3.802	8.032
Location	[Anoxic=0]	-.652	.450	2.098	1	.147	-1.535	.230
	[Anoxic=1]	0[a]	.	.	0	.	.	.
	[Phase2Num2=1]	.392	.466	.706	1	.401	-.522	1.306
	[Phase2Num2=2]	0[a]	.	.	0	.	.	.
	[StandardSoilNum=1]	2.890	1.218	5.631	1	.018	.503	5.277
	[StandardSoilNum=2]	2.100	1.240	2.865	1	.091	-.332	4.531
	[StandardSoilNum=3]	2.980	1.225	5.915	1	.015	.578	5.382
	[StandardSoilNum=4]	.731	1.076	.462	1	.497	-1.378	2.840
	[StandardSoilNum=5]	0[a]	.	.	0	.	.	.
	[Cave=0]	-2.147	1.058	4.120	1	.042	-4.221	-.074
	[Cave=1]	0[a]	.	.	0	.	.	.
	[BD=0]	-.790	.501	2.491	1	.115	-1.772	.191
	[BD=1]	0[a]	.	.	0	.	.	.
	[State2Num=1.00]	1.042	.502	4.314	1	.038	.059	2.026
	[State2Num=2.00]	0[a]	.	.	0	.	.	.
	[Charnel=0]	1.209	.429	7.938	1	.005	.368	2.051
	[Charnel=1]	0[a]	.	.	0	.	.	.
	[AgeRange4Num=1.00]	.984	.475	4.290	1	.038	.053	1.916
	[AgeRange4Num=2.00]	.141	.474	.089	1	.766	-.787	1.069
	[AgeRange4Num=3.00]	.570	.432	1.744	1	.187	-.276	1.416
	[AgeRange4Num=4.00]	0[a]	.	.	0	.	.	.

Link function: Logit.

a. This parameter is set to zero because it is redundant.

Test of Parallel Lines[a]

Model	-2 Log Likelihood	Chi-Square	df	Sig.
Null Hypothesis	192.184			
General	122.290[b]	69.894[c]	26	.000

The null hypothesis states that the location parameters (slope coefficients) are the same across response categories.

a. Link function: Logit.

b. The log-likelihood value cannot be further increased after maximum number of step-halving.

c. The Chi-Square statistic is computed based on the log-likelihood value of the last iteration of the general model. Validity of the test is uncertain.

11.8.3 Orange Inclusions Ordinal Regression Model 3

Case Processing Summary

		N	Marginal Percentage
Orange Inclusions	None	46	17.3%
	Infrequent	124	46.6%
	Frequent	93	35.0%
	Pervasive	3	1.1%
Soil Type	Clay	124	46.6%
	Gravel	65	24.4%
	Sand	24	9.0%
	Silt	35	13.2%
	Open	18	6.8%
Cave	Non-Cave	244	91.7%
	Cave	22	8.3%
State	Articulated	203	76.3%
	Disarticulated	63	23.7%
Charnel	Non-Charnel	213	80.1%
	Charnel	53	19.9%
Age Range	Neonate	29	10.9%
	Child	20	7.5%
	Juvenile	24	9.0%
	Adult	193	72.6%
Valid		266	100.0%
Missing		35	
Total		301	

Model Fitting Information

Model	-2 Log Likelihood	Chi-Square	df	Sig.
Intercept Only	196.735			
Final	144.060	52.676	10	.000

Link function: Logit.

Goodness-of-Fit

	Chi-Square	df	Sig.
Pearson	82.388	77	.316
Deviance	74.130	77	.572

Link function: Logit.

Pseudo R-Square

Cox and Snell	.180
Nagelkerke	.203
McFadden	.092

Link function: Logit.

Parameter Estimates

		Estimate	Std. Error	Wald	df	Sig.	95% Confidence Interval	
							Lower Bound	Upper Bound
Threshold	[OrangeInc = 0]	.264	.588	.202	1	.653	-.888	1.416
	[OrangeInc = 1]	2.754	.616	20.006	1	.000	1.547	3.960
	[OrangeInc = 2]	6.878	.865	63.291	1	.000	5.183	8.572
Location	[StandardSoilNum=1]	2.855	1.208	5.592	1	.018	.489	5.222
	[StandardSoilNum=2]	2.149	1.200	3.208	1	.073	-.202	4.500
	[StandardSoilNum=3]	2.904	1.217	5.693	1	.017	.519	5.290
	[StandardSoilNum=4]	.775	1.072	.522	1	.470	-1.326	2.876
	[StandardSoilNum=5]	0[a]	.	.	0	.	.	.
	[Cave=0]	-2.145	1.053	4.148	1	.042	-4.210	-.081
	[Cave=1]	0[a]	.	.	0	.	.	.
	[State2Num=1.00]	.890	.446	3.983	1	.046	.016	1.765
	[State2Num=2.00]	0[a]	.	.	0	.	.	.
	[Charnel=0]	1.205	.390	9.559	1	.002	.441	1.969
	[Charnel=1]	0[a]	.	.	0	.	.	.
	[AgeRange4Num=1.00]	.794	.453	3.078	1	.079	-.093	1.682
	[AgeRange4Num=2.00]	-.030	.464	.004	1	.948	-.939	.879
	[AgeRange4Num=3.00]	.487	.426	1.312	1	.252	-.347	1.322
	[AgeRange4Num=4.00]	0[a]	.	.	0	.	.	.

Link function: Logit.

a. This parameter is set to zero because it is redundant.

Test of Parallel Lines[a]

Model	-2 Log Likelihood	Chi-Square	df	Sig.
Null Hypothesis	144.060			
General	113.053[b]	31.007[c]	20	.055

The null hypothesis states that the location parameters (slope coefficients) are the same across response categories.

a. Link function: Logit.

b. The log-likelihood value cannot be further increased after maximum number of step-halving.

c. The Chi-Square statistic is computed based on the log-likelihood value of the last iteration of the general model. Validity of the test is uncertain.

11.8.4 Orange Inclusions Ordinal Regression Model 4

Case Processing Summary

		N	Marginal Percentage
Orange Inclusions	None	46	17.3%
	Infrequent	124	46.6%
	Frequent	93	35.0%
	Pervasive	3	1.1%
Soil Type	Clay	124	46.6%
	Gravel	65	24.4%
	Sand	24	9.0%
	Silt	35	13.2%
	Open	18	6.8%
Cave	Non-Cave	244	91.7%
	Cave	22	8.3%
State	Articulated	203	76.3%
	Disarticulated	63	23.7%
Charnel	Non-Charnel	213	80.1%
	Charnel	53	19.9%
Valid		266	100.0%
Missing		35	
Total		301	

Model Fitting Information

Model	-2 Log Likelihood	Chi-Square	df	Sig.
Intercept Only	142.322			
Final	94.262	48.060	7	.000

Link function: Logit.

Goodness-of-Fit

	Chi-Square	df	Sig.
Pearson	41.417	23	.011
Deviance	37.260	23	.031

Link function: Logit.

Pseudo R-Square

Cox and Snell	.165
Nagelkerke	.187
McFadden	.084

Link function: Logit.

Parameter Estimates

		Estimate	Std. Error	Wald	df	Sig.	95% Confidence Interval	
							Lower Bound	Upper Bound
Threshold	[OrangeInc = 0]	.307	.576	.284	1	.594	-.822	1.436
	[OrangeInc = 1]	2.773	.604	21.067	1	.000	1.589	3.957
	[OrangeInc = 2]	6.846	.854	64.269	1	.000	5.172	8.520
Location	[StandardSoilNum=1]	3.018	1.184	6.496	1	.011	.697	5.338
	[StandardSoilNum=2]	2.113	1.190	3.151	1	.076	-.220	4.446
	[StandardSoilNum=3]	2.968	1.207	6.048	1	.014	.602	5.333
	[StandardSoilNum=4]	.781	1.059	.545	1	.461	-1.294	2.856
	[StandardSoilNum=5]	0[a]	.	.	0	.	.	.
	[Cave=0]	-2.257	1.035	4.758	1	.029	-4.286	-.229
	[Cave=1]	0[a]	.	.	0	.	.	.
	[State2Num=1.00]	.952	.437	4.749	1	.029	.096	1.808
	[State2Num=2.00]	0[a]	.	.	0	.	.	.
	[Charnel=0]	1.372	.362	14.341	1	.000	.662	2.083
	[Charnel=1]	0[a]	.	.	0	.	.	.

Link function: Logit.

a. This parameter is set to zero because it is redundant.

Test of Parallel Lines[a]

Model	-2 Log Likelihood	Chi-Square	df	Sig.
Null Hypothesis	94.262			
General	82.086[b]	12.176[c]	14	.592

The null hypothesis states that the location parameters (slope coefficients) are the same across response categories.

a. Link function: Logit.

b. The log-likelihood value cannot be further increased after maximum number of step-halving.

c. The Chi-Square statistic is computed based on the log-likelihood value of the last iteration of the general model. Validity of the test is uncertain.

11.8.5 Orange Inclusions Ordinal Regression Model 5

Case Processing Summary

		N	Marginal Percentage
Orange Inclusions	None	46	17.3%
	Infrequent	124	46.6%
	Frequent	93	35.0%
	Pervasive	3	1.1%
Soil Type	Clay	124	46.6%
	Gravel	65	24.4%
	Sand	24	9.0%
	Silt	35	13.2%
Charnel	Open	18	6.8%
	Non-Charnel	213	80.1%
	Charnel	53	19.9%
Valid		266	100.0%
Missing		35	
Total		301	

Model Fitting Information

Model	-2 Log Likelihood	Chi-Square	df	Sig.
Intercept Only	104.592			
Final	65.236	39.356	5	.000

Link function: Logit.

Goodness-of-Fit

	Chi-Square	df	Sig.
Pearson	17.898	10	.057
Deviance	17.432	10	.065

Link function: Logit.

Pseudo R-Square

Cox and Snell	.138
Nagelkerke	.156
McFadden	.069

Link function: Logit.

Parameter Estimates

		Estimate	Std. Error	Wald	df	Sig.	95% Confidence Interval	
							Lower Bound	Upper Bound
Threshold	[OrangeInc = 0]	.204	.571	.128	1	.721	-.915	1.323
	[OrangeInc = 1]	2.614	.597	19.182	1	.000	1.444	3.783
	[OrangeInc = 2]	6.645	.844	62.052	1	.000	4.991	8.298
Location	[StandardSoilNum=1]	1.578	.515	9.400	1	.002	.569	2.586
	[StandardSoilNum=2]	.773	.512	2.282	1	.131	-.230	1.777
	[StandardSoilNum=3]	1.256	.602	4.362	1	.037	.077	2.435
	[StandardSoilNum=4]	-.895	.558	2.575	1	.109	-1.989	.198
	[StandardSoilNum=5]	0[a]	.	.	0	.	.	.
	[Charnel=0]	1.245	.356	12.235	1	.000	.547	1.942
	[Charnel=1]	0[a]	.	.	0	.	.	.

Link function: Logit.
a. This parameter is set to zero because it is redundant.

Test of Parallel Lines[a]

Model	-2 Log Likelihood	Chi-Square	df	Sig.
Null Hypothesis	65.236			
General	47.804	17.432	10	.065

The null hypothesis states that the location parameters (slope coefficients) are the same across response categories.
a. Link function: Logit.

11.8.6 Orange Inclusions Ordinal Regression Model 6

Case Processing Summary

		N	Marginal Percentage
Orange Inclusions	None	46	17.3%
	Infrequent	124	46.6%
	Frequent	93	35.0%
	Pervasive	3	1.1%
Charnel	Non-Charnel	213	80.1%
	Charnel	53	19.9%
Valid		266	100.0%
Missing		35	
Total		301	

Model Fitting Information

Model	-2 Log Likelihood	Chi-Square	df	Sig.
Intercept Only	28.310			
Final	25.959	2.351	1	.125

Link function: Logit.

Goodness-of-Fit

	Chi-Square	df	Sig.
Pearson	2.776	2	.250
Deviance	2.575	2	.276

Link function: Logit.

Pseudo R-Square

Cox and Snell	.009
Nagelkerke	.010
McFadden	.004

Link function: Logit.

Parameter Estimates

		Estimate	Std. Error	Wald	df	Sig.	95% Confidence Interval	
							Lower Bound	Upper Bound
Threshold	[OrangeInc = 0]	-1.230	.275	20.014	1	.000	-1.769	-.691
	[OrangeInc = 1]	.923	.269	11.778	1	.001	.396	1.450
	[OrangeInc = 2]	4.838	.630	58.926	1	.000	3.603	6.073
Location	[Charnel=0]	.437	.290	2.274	1	.132	-.131	1.004
	[Charnel=1]	0[a]	.	.	0	.	.	.

Link function: Logit.

a. This parameter is set to zero because it is redundant.

Test of Parallel Lines[a]

Model	-2 Log Likelihood	Chi-Square	df	Sig.
Null Hypothesis	25.959			
General	23.384	2.575	2	.276

The null hypothesis states that the location parameters (slope coefficients) are the same across response categories.

a. Link function: Logit.

11.9 GREY INCLUSIONS

11.9.1 Grey Inclusions Ordinal Regression Model 1

Case Processing Summary

		N	Marginal Percentage
Grey Inclusions	None	105	89.7%
	Infrequent	12	10.3%
Anoxic	Absent	106	90.6%
	Present	11	9.4%
Phase	Later Prehistoric	40	34.2%
	Historical	77	65.8%
Soil Type	Clay	30	25.6%
	Gravel	55	47.0%
	Sand	16	13.7%
	Silt	13	11.1%
	Open	3	2.6%
Cave	Non-Cave	114	97.4%
	Cave	3	2.6%
Black Death	Non-Black Death	95	81.2%
	Black Death	22	18.8%
State	Articulated	99	84.6%
	Disarticulated	18	15.4%
Charnel	Non-Charnel	115	98.3%
	Charnel	2	1.7%
Sex	Male	62	53.0%
	Female	55	47.0%
Age Range	Juvenile	12	10.3%
	Adult	105	89.7%
Valid		117	100.0%
Missing		184	
Total		301	

Model Fitting Information

Model	-2 Log Likelihood	Chi-Square	df	Sig.
Intercept Only	74.160			
Final	.000	74.160	11	.000

Link function: Logit.

Goodness-of-Fit

	Chi-Square	df	Sig.
Pearson	.[a]	23	.
Deviance	.[a]	23	.

Link function: Logit.

a. Floating point overflow occurred while computing this statistic. Its value is therefore set to system missing.

Pseudo R-Square

Cox and Snell	.469
Nagelkerke	.970
McFadden	.958

Link function: Logit.

Parameter Estimates

		Estimate	Std. Error	Wald	df	Sig.	95% Confidence Interval	
							Lower Bound	Upper Bound
Threshold	[GreyInc = 0]	4.439	8.499	.273	1	.601	-12.218	21.095
	[Anoxic=0]	.062	3.513	.000	1	.986	-6.825	6.948
	[Anoxic=1]	0[a]	.	.	0	.	.	.
	[Phase2Num2=1]	.496	2.380	.043	1	.835	-4.169	5.160
	[Phase2Num2=2]	0[a]	.	.	0	.	.	.
	[StandardSoilNum=1]	-2.646	9.408	.079	1	.778	-21.086	15.793
	[StandardSoilNum=2]	-2.499	9.287	.072	1	.788	-20.701	15.702
	[StandardSoilNum=3]	-2.333	9.015	.067	1	.796	-20.001	15.336
	[StandardSoilNum=4]	-51.969	.000	.	1	.	-51.969	-51.969
	[StandardSoilNum=5]	0[a]	.	.	0	.	.	.
	[Cave=0]	0[a]	.	.	0	.	.	.
Location	[Cave=1]	0[a]	.	.	0	.	.	.
	[BD=0]	-.085	2.384	.001	1	.972	-4.758	4.588
	[BD=1]	0[a]	.	.	0	.	.	.
	[State2Num=1.00]	2.469	7.529	.108	1	.743	-12.288	17.226
	[State2Num=2.00]	0[a]	.	.	0	.	.	.
	[Charnel=0]	-.355	6.817	.003	1	.958	-13.715	13.006
	[Charnel=1]	0[a]	.	.	0	.	.	.
	[SexNum=1]	.714	1.880	.144	1	.704	-2.972	4.399
	[SexNum=2]	0[a]	.	.	0	.	.	.
	[AgeRange4Num=3.00]	.999	2.395	.174	1	.677	-3.695	5.693
	[AgeRange4Num=4.00]	0[a]	.	.	0	.	.	.

Link function: Logit.

a. This parameter is set to zero because it is redundant.

Test of Parallel Lines[a]

Model	-2 Log Likelihood	Chi-Square	df	Sig.
Null Hypothesis	.000			
General	.000[b]	.000	0	.

The null hypothesis states that the location parameters (slope coefficients) are the same across response categories.

a. Link function: Logit.

b. The log-likelihood value is practically zero. There may be a complete separation in the data. The maximum likelihood estimates do not exist.

11.9.2 Grey Inclusions Ordinal Regression Model 2

Case Processing Summary

		N	Marginal Percentage
Grey Inclusions	None	246	92.5%
	Infrequent	19	7.1%
	Frequent	1	0.4%
Anoxic	Absent	240	90.2%
	Present	26	9.8%
Phase	Later Prehistoric	93	35.0%
	Historical	173	65.0%
Soil Type	Clay	124	46.6%
	Gravel	65	24.4%
	Sand	24	9.0%
	Silt	35	13.2%
	Open	18	6.8%
Cave	Non-Cave	244	91.7%
	Cave	22	8.3%
Black Death	Non-Black Death	241	90.6%
	Black Death	25	9.4%
State	Articulated	203	76.3%
	Disarticulated	63	23.7%
Charnel	Non-Charnel	213	80.1%
	Charnel	53	19.9%
Age Range	Neonate	29	10.9%
	Child	20	7.5%
	Juvenile	24	9.0%
	Adult	193	72.6%
Valid		266	100.0%
Missing		35	
Total		301	

Model Fitting Information

Model	-2 Log Likelihood	Chi-Square	df	Sig.
Intercept Only	101.727			
Final	23.993	77.734	13	.000

Link function: Logit.

Goodness-of-Fit

	Chi-Square	df	Sig.
Pearson	47.297	73	.992
Deviance	12.212	73	1.000

Link function: Logit.

Pseudo R-Square

Cox and Snell	.253
Nagelkerke	.588
McFadden	.519

Link function: Logit.

Parameter Estimates

		Estimate	Std. Error	Wald	df	Sig.	95% Confidence Interval	
							Lower Bound	Upper Bound
Threshold	[GreyInc = 0]	2.324	2987.899	.000	1	.999	-5853.850	5858.499
	[GreyInc = 1]	6.188	2987.899	.000	1	.998	-5849.987	5862.364
Location	[Anoxic=0]	14.716	1542.928	.000	1	.992	-3009.366	3038.799
	[Anoxic=1]	0[a]	.	.	0	.	.	.
	[Phase2Num2=1]	.086	1617.017	.000	1	1.000	-3169.210	3169.381
	[Phase2Num2=2]	0[a]	.	.	0	.	.	.
	[StandardSoilNum=1]	-34.146	1414.385	.001	1	.981	-2806.289	2737.998
	[StandardSoilNum=2]	-34.778	2018.357	.000	1	.986	-3990.685	3921.128
	[StandardSoilNum=3]	-34.185	1899.835	.000	1	.986	-3757.793	3689.423
	[StandardSoilNum=4]	-15.703	1.090	207.440	1	.000	-17.839	-13.566
	[StandardSoilNum=5]	0[a]	.	.	0	.	.	.
	[Cave=0]	18.147	.000	.	1	.	18.147	18.147
	[Cave=1]	0[a]	.	.	0	.	.	.
	[BD=0]	-.273	2185.908	.000	1	1.000	-4284.574	4284.028
	[BD=1]	0[a]	.	.	0	.	.	.
	[State2Num=1.00]	.969	.870	1.243	1	.265	-.735	2.674
	[State2Num=2.00]	0[a]	.	.	0	.	.	.
	[Charnel=0]	-14.865	1076.405	.000	1	.989	-2124.580	2094.849
	[Charnel=1]	0[a]	.	.	0	.	.	.
	[AgeRange4Num=1.00]	-12.694	1294.815	.000	1	.992	-2550.485	2525.097
	[AgeRange4Num=2.00]	1.301	1.420	.840	1	.359	-1.481	4.084
	[AgeRange4Num=3.00]	.269	1.006	.072	1	.789	-1.702	2.241
	[AgeRange4Num=4.00]	0[a]	.	.	0	.	.	.

Link function: Logit.

a. This parameter is set to zero because it is redundant.

Test of Parallel Lines[a]

Model	-2 Log Likelihood	Chi-Square	df	Sig.
Null Hypothesis	23.993			
General	.000[b]	23.993	13	.031

The null hypothesis states that the location parameters (slope coefficients) are the same across response categories.

a. Link function: Logit.

b. The log-likelihood value is practically zero. There may be a complete separation in the data. The maximum likelihood estimates do not exist.

11.9.3 Grey Inclusions Ordinal Regression Model 3

Case Processing Summary

		N	Marginal Percentage
Grey Inclusions	None	246	92.5%
	Infrequent	19	7.1%
	Frequent	1	0.4%
Soil Type	Clay	124	46.6%
	Gravel	65	24.4%
	Sand	24	9.0%
	Silt	35	13.2%
State	Open	18	6.8%
	Articulated	203	76.3%
	Disarticulated	63	23.7%
Age Range	Neonate	29	10.9%
	Child	20	7.5%
	Juvenile	24	9.0%
	Adult	193	72.6%
Valid		266	100.0%
Missing		35	
Total		301	

Model Fitting Information

Model	-2 Log Likelihood	Chi-Square	df	Sig.
Intercept Only	94.680			
Final	.000	94.680	8	.000

Link function: Logit.

Goodness-of-Fit

	Chi-Square	df	Sig.
Pearson	42.649	38	.278
Deviance	11.815	38	1.000

Link function: Logit.

Pseudo R-Square

Cox and Snell	.299
Nagelkerke	.695
McFadden	.632

Link function: Logit.

Parameter Estimates

		Estimate	Std. Error	Wald	df	Sig.	95% Confidence Interval	
							Lower Bound	Upper Bound
Threshold	[GreyInc = 0]	2.685	1.009	7.075	1	.008	.706	4.663
	[GreyInc = 1]	6.420	1.461	19.324	1	.000	3.558	9.283
Location	[StandardSoilNum=1]	-2.531	1.492	2.877	1	.090	-5.455	.393
	[StandardSoilNum=2]	-17.820	1754.239	.000	1	.992	-3456.066	3420.426
	[StandardSoilNum=3]	-17.382	2790.597	.000	1	.995	-5486.851	5452.087
	[StandardSoilNum=4]	2.257	1.084	4.335	1	.037	.132	4.382
	[StandardSoilNum=5]	0[a]	.	.	0	.	.	.
	[State2Num=1.00]	1.311	.845	2.409	1	.121	-.344	2.967
	[State2Num=2.00]	0[a]	.	.	0	.	.	.
	[AgeRange4Num=1.00]	-15.824	2400.935	.000	1	.995	-4721.570	4689.923
	[AgeRange4Num=2.00]	.217	1.070	.041	1	.839	-1.879	2.313
	[AgeRange4Num=3.00]	.533	1.013	.276	1	.599	-1.453	2.519
	[AgeRange4Num=4.00]	0[a]	.	.	0	.	.	.

Link function: Logit.
a. This parameter is set to zero because it is redundant.

Test of Parallel Lines[a]

Model	-2 Log Likelihood	Chi-Square	df	Sig.
Null Hypothesis	.000			
General	20.459[b]	.[c]	8	.

The null hypothesis states that the location parameters (slope coefficients) are the same across response categories.
a. Link function: Logit.
b. The log-likelihood value cannot be further increased after maximum number of step-halving.
c. The log-likelihood value of the general model is smaller than that of the null model. This is because convergence cannot be attained or ascertained in estimating the general model. Therefore, the test of parallel lines cannot be performed.

11.9.4 Grey Inclusions Ordinal Regression Model 4

Case Processing Summary

		N	Marginal Percentage
Grey Inclusions	None	246	92.5%
	Infrequent	19	7.1%
	Frequent	1	0.4%
Soil Type	Clay	124	46.6%
	Gravel	65	24.4%
	Sand	24	9.0%
	Silt	35	13.2%
	Open	18	6.8%
Valid		266	100.0%
Missing		35	
Total		301	

Model Fitting Information

Model	-2 Log Likelihood	Chi-Square	df	Sig.
Intercept Only	81.778			
Final	17.545	64.233	4	.000

Link function: Logit.

Goodness-of-Fit

	Chi-Square	df	Sig.
Pearson	30.957	4	.000
Deviance	8.983	4	.062

Link function: Logit.

Pseudo R-Square

Cox and Snell	.215
Nagelkerke	.498
McFadden	.428

Link function: Logit.

Parameter Estimates

		Estimate	Std. Error	Wald	df	Sig.	95% Confidence Interval	
							Lower Bound	Upper Bound
Threshold	[GreyInc = 0]	2.775	1.003	7.659	1	.006	.810	4.739
	[GreyInc = 1]	6.317	1.427	19.594	1	.000	3.520	9.114
Location	[StandardSoilNum=1]	-1.337	1.230	1.181	1	.277	-3.748	1.074
	[StandardSoilNum=2]	-19.348	7897.470	.000	1	.998	-15498.105	15459.408
	[StandardSoilNum=3]	-19.348	.000	.	1	.	-19.348	-19.348
	[StandardSoilNum=4]	2.668	1.058	6.360	1	.012	.594	4.742
	[StandardSoilNum=5]	0[a]	.	.	0	.	.	.

Link function: Logit.
a. This parameter is set to zero because it is redundant.

Test of Parallel Lines[a]

Model	-2 Log Likelihood	Chi-Square	df	Sig.
Null Hypothesis	17.545			
General	.000[b]	17.545	4	.002

The null hypothesis states that the location parameters (slope coefficients) are the same across response categories.
a. Link function: Logit.
b. The log-likelihood value is practically zero. There may be a complete separation in the data. The maximum likelihood estimates do not exist.

11.10 INFILTRATIONS

11.10.1 Infiltrations Binary Logistic Regression Model 1

Case Processing Summary

Unweighted Cases[a]		N	Percent
Selected Cases	Included in Analysis	117	38.9
	Missing Cases	184	61.1
	Total	301	100.0
Unselected Cases		0	.0
Total		301	100.0

a. If weight is in effect, see classification table for the total number of cases.

Omnibus Tests of Model Coefficients

		Chi-square	df	Sig.
Step 1	Step	38.037	11	.000
	Block	38.037	11	.000
	Model	38.037	11	.000

Model Summary

Step	-2 Log likelihood	Cox & Snell R Square	Nagelkerke R Square
1	123.945[a]	.278	.370

a. Estimation terminated at iteration number 20 because maximum iterations has been reached. Final solution cannot be found.

Hosmer and Lemeshow Test

Step	Chi-square	df	Sig.
1	9.981	8	.266

Contingency Table for Hosmer and Lemeshow Test

		Infiltrations = Absent		Infiltrations = Present		Total
		Observed	Expected	Observed	Expected	
Step 1	1	10	11.479	2	.521	12
	2	13	11.651	0	1.349	13
	3	10	8.592	1	2.408	11
	4	6	5.765	4	4.235	10
	5	5	4.848	6	6.152	11
	6	5	4.313	6	6.687	11
	7	4	5.091	9	7.909	13
	8	3	3.451	7	6.549	10
	9	1	2.936	9	7.064	10
	10	4	2.874	12	13.126	16

Classification Table[a]

	Observed		Predicted		
			Infiltrations		Percentage Correct
			Absent	Present	
Step 1	Infiltrations	Absent	38	23	62.3
		Present	7	49	87.5
	Overall Percentage				74.4

a. The cut value is .500

Variables in the Equation

		B	S.E.	Wald	df	Sig.	Exp(B)
Step 1[a]	Anoxic(1)	2.522	1.070	5.555	1	.018	12.455
	Phase2Num2(1)	-.915	.799	1.312	1	.252	.400
	StandardSoilNum			16.408	4	.003	
	StandardSoilNum(1)	22.291	23205.450	.000	1	.999	4797871286.819
	StandardSoilNum(2)	20.651	23205.450	.000	1	.999	930594683.836
	StandardSoilNum(3)	18.563	23205.450	.000	1	.999	115325979.791
	StandardSoilNum(4)	18.556	23205.450	.000	1	.999	114542317.722
	BD(1)	-.200	.582	.118	1	.731	.819
	State2Num(1)	-.125	1.110	.013	1	.910	.882
	Charnel(1)	-.543	1.609	.114	1	.736	.581
	SexNum(1)	.202	.455	.198	1	.657	1.224
	AgeRange4Num(1)	.535	.765	.489	1	.484	1.707
	Constant	-22.067	23205.451	.000	1	.999	.000

a. Variable(s) entered on step 1: Anoxic, Phase2Num2, StandardSoilNum, BD, State2Num, Charnel, SexNum, AgeRange4Num.

11.10.2 Infiltrations Binary Logistic Regression Model 2

Case Processing Summary

Unweighted Cases[a]		N	Percent
Selected Cases	Included in Analysis	266	88.4
	Missing Cases	35	11.6
	Total	301	100.0
Unselected Cases		0	.0
Total		301	100.0

a. If weight is in effect, see classification table for the total number of cases.

Omnibus Tests of Model Coefficients

		Chi-square	df	Sig.
Step 1	Step	68.448	13	.000
	Block	68.448	13	.000
	Model	68.448	13	.000

Model Summary

Step	-2 Log likelihood	Cox & Snell R Square	Nagelkerke R Square
1	275.869[a]	.227	.313

a. Estimation terminated at iteration number 6 because parameter estimates changed by less than .001.

Hosmer and Lemeshow Test

Step	Chi-square	df	Sig.
1	2.647	8	.955

Contingency Table for Hosmer and Lemeshow Test

		Infiltrations = Absent		Infiltrations = Present		Total
		Observed	Expected	Observed	Expected	
Step 1	1	22	22.740	2	1.260	24
	2	26	25.184	1	1.816	27
	3	19	19.820	4	3.180	23
	4	12	11.655	2	2.345	14
	5	23	22.390	6	6.610	29
	6	21	20.392	6	6.608	27
	7	12	13.866	12	10.134	24
	8	15	13.685	17	18.315	32
	9	10	11.530	21	19.470	31
	10	13	11.739	22	23.261	35

Classification Table[a]

	Observed		Predicted		
			Infiltrations		Percentage Correct
			Absent	Present	
Step 1	Infiltrations	Absent	132	41	76.3
		Present	28	65	69.9
	Overall Percentage				74.1

a. The cut value is .500

Variables in the Equation

		B	S.E.	Wald	df	Sig.	Exp(B)
Step 1[a]	Anoxic(1)	.573	.563	1.034	1	.309	1.773
	Phase2Num2(1)	.241	.552	.191	1	.662	1.272
	StandardSoilNum			21.167	4	.000	
	StandardSoilNum(1)	4.924	1.798	7.502	1	.006	137.523
	StandardSoilNum(2)	5.243	1.823	8.270	1	.004	189.160
	StandardSoilNum(3)	2.998	1.830	2.684	1	.101	20.041
	StandardSoilNum(4)	1.945	1.577	1.521	1	.217	6.991
	Cave(1)	-1.974	1.412	1.955	1	.162	.139
	BD(1)	-.025	.545	.002	1	.964	.976
	State2Num(1)	.289	.660	.192	1	.662	1.335
	Charnel(1)	1.432	.511	7.866	1	.005	4.186
	AgeRange4Num			6.232	3	.101	
	AgeRange4Num(1)	-1.324	.607	4.757	1	.029	.266
	AgeRange4Num(2)	-.032	.554	.003	1	.955	.969
	AgeRange4Num(3)	.549	.527	1.082	1	.298	1.731
	Constant	-5.007	1.389	12.988	1	.000	.007

a. Variable(s) entered on step 1: Anoxic, Phase2Num2, StandardSoilNum, Cave, BD, State2Num, Charnel, AgeRange4Num.

11.10.3 Infiltrations Binary Logistic Regression Model 3

Case Processing Summary

Unweighted Cases[a]		N	Percent
Selected Cases	Included in Analysis	266	88.4
	Missing Cases	35	11.6
	Total	301	100.0
Unselected Cases		0	.0
Total		301	100.0

a. If weight is in effect, see classification table for the total number of cases.

Omnibus Tests of Model Coefficients

		Chi-square	df	Sig.
Step 1	Step	65.490	8	.000
	Block	65.490	8	.000
	Model	65.490	8	.000

Model Summary

Step	-2 Log likelihood	Cox & Snell R Square	Nagelkerke R Square
1	278.828[a]	.218	.301

a. Estimation terminated at iteration number 6 because parameter estimates changed by less than .001.

Hosmer and Lemeshow Test

Step	Chi-square	df	Sig.
1	4.773	7	.688

Contingency Table for Hosmer and Lemeshow Test

		Infiltrations = Absent		Infiltrations = Present		Total
		Observed	Expected	Observed	Expected	
Step 1	1	20	19.886	1	1.114	21
	2	25	25.680	3	2.320	28
	3	22	21.475	3	3.525	25
	4	34	34.342	9	8.658	43
	5	23	22.652	7	7.348	30
	6	19	21.244	24	21.756	43
	7	6	4.050	3	4.950	9
	8	22	19.429	31	33.571	53
	9	2	4.242	12	9.758	14

Classification Table[a]

			Predicted		
			Infiltrations		Percentage Correct
			Absent	Present	
Step 1	Infiltrations	Absent	128	45	74.0
		Present	25	68	73.1
	Overall Percentage				73.7

a. The cut value is .500

Variables in the Equation

		B	S.E.	Wald	df	Sig.	Exp(B)
Step 1[a]	StandardSoilNum			36.247	4	.000	
	StandardSoilNum(1)	2.945	1.073	7.535	1	.006	19.006
	StandardSoilNum(2)	3.333	1.065	9.802	1	.002	28.023
	StandardSoilNum(3)	1.082	1.174	.850	1	.357	2.950
	StandardSoilNum(4)	.382	1.197	.102	1	.750	1.465
	Charnel(1)	1.537	.452	11.530	1	.001	4.648
	AgeRange4Num			6.639	3	.084	
	AgeRange4Num(1)	-1.256	.552	5.171	1	.023	.285
	AgeRange4Num(2)	.042	.534	.006	1	.937	1.043
	AgeRange4Num(3)	.524	.519	1.020	1	.312	1.689
	Constant	-4.323	1.127	14.710	1	.000	.013

a. Variable(s) entered on step 1: StandardSoilNum, Charnel, AgeRange4Num.

11.10.4 Infiltrations Binary Logistic Regression Model 4

Case Processing Summary

Unweighted Cases[a]		N	Percent
Selected Cases	Included in Analysis	266	88.4
	Missing Cases	35	11.6
	Total	301	100.0
Unselected Cases		0	.0
Total		301	100.0

a. If weight is in effect, see classification table for the total number of cases.

Omnibus Tests of Model Coefficients

		Chi-square	df	Sig.
Step 1	Step	15.666	1	.000
	Block	15.666	1	.000
	Model	15.666	1	.000

Model Summary

Step	-2 Log likelihood	Cox & Snell R Square	Nagelkerke R Square
1	328.652[a]	.057	.079

a. Estimation terminated at iteration number 4 because parameter estimates changed by less than .001.

Hosmer and Lemeshow Test

Step	Chi-square	df	Sig.
1	.000	3	1.000

Contingency Table for Hosmer and Lemeshow Test

		Infiltrations = Absent		Infiltrations = Present		Total
		Observed	Expected	Observed	Expected	
Step 1	1	17	17.000	1	1.000	18
	2	32	32.000	3	3.000	35
	3	20	20.000	4	4.000	24
	4	81	81.000	43	43.000	124
	5	23	23.000	42	42.000	65

Classification Table[a]

	Observed		Predicted		
			Infiltrations		Percentage Correct
			Absent	Present	
Step 1	Infiltrations	Absent	173	0	100.0
		Present	93	0	.0
	Overall Percentage				65.0

a. The cut value is .500

Variables in the Equation

		B	S.E.	Wald	df	Sig.	Exp(B)
Step 1[a]	StandardSoilNum	-.433	.118	13.537	1	.000	.649
	Constant	.229	.253	.823	1	.364	1.257

a. Variable(s) entered on step 1: StandardSoilNum.

12 APPENDIX 2: HOLM-BONFERRONI METHOD

The following table presents all of the p-values of statistical tests run on pairs of variables for the current study and the assessment of their significance using the Holm-Bonferroni correction for multiplicity. A p-value was significant when it was below the threshold defined by the Holm-Bonferroni method. Significant p-values are highlighted in bold.

TEST NO.	COMPARISON	TEST	P-VALUE	HOLM-BONFERRONI SIGNIFICANCE THRESHOLD
1	Presence of Bacterial Attack & Cave Deposition	Binary Logistic Regression	1.000	0.050
2	Persistence of the Periosteal Surface & Black Death	Binary Logistic Regression	1.000	0.025
3	Brown Staining & Clay Soil Type	Ordinal Regression	1.000	0.017
4	Brown Staining & Silt Soil Type	Ordinal Regression	1.000	0.013
5	Grey Inclusions & Phase	Ordinal Regression	1.000	0.010
6	Grey Inclusions & Black Death	Ordinal Regression	1.000	0.008
7	Persistence of the Periosteal Surface & Cave Deposition	Binary Logistic Regression	0.999	0.007
8	Brown Staining & Gravel Soil Type	Ordinal Regression	0.999	0.006
9	Brown Staining & Sand Soil Type	Ordinal Regression	0.999	0.006
10	Persistence of the Periosteal Surface & Anoxia	Binary Logistic Regression	0.998	0.005
11	Yellow Staining & Child Age Category	Ordinal Regression	0.992	0.005
12	Grey Inclusions & Anoxia	Ordinal Regression	0.992	0.004
13	Grey Inclusions & Neonatal Age Category	Ordinal Regression	0.992	0.004
14	Brown Staining & Child Age Category	Ordinal Regression	0.990	0.004
15	Yellow Staining & Black Death	Ordinal Regression	0.989	0.003
16	Grey Inclusions & Charnel	Ordinal Regression	0.989	0.003
17	Grey Inclusions & Gravel Soil Type	Ordinal Regression	0.986	0.003
18	Grey Inclusions & Sand Soil Type	Ordinal Regression	0.986	0.003
19	Grey Inclusions & Clay Soil Type	Ordinal Regression	0.981	0.003
20	Whole OHI & Sand Soil Type	Ordinal Regression	0.977	0.003
21	Yellow Staining & Phase	Ordinal Regression	0.968	0.002
22	Infiltrations & Black Death	Binary Logistic Regression	0.964	0.002

TEST NO.	COMPARISON	TEST	P-VALUE	HOLM-BONFERRONI SIGNIFICANCE THRESHOLD
23	Yellow Staining & Neonatal Age Category	Ordinal Regression	0.962	0.002
24	Orange Inclusions & Sex	Ordinal Regression	0.952	0.002
25	Yellow Staining & Orange Inclusions	Ordinal Regression	0.950	0.002
26	Wedl Tunnelling & Anoxia	Binary Logistic Regression	0.935	0.002
27	Yellow Staining & Silt Site Assemblages	Kruskal-Wallis	0.918	0.002
28	Persistence of the Periosteal Surface & Charnel	Binary Logistic Regression	0.916	0.002
29	Yellow Staining & Gravel Soil Type	Ordinal Regression	0.905	0.002
30	Yellow Staining & Clay Soil Type	Ordinal Regression	0.897	0.002
31	Persistence of the Periosteal Surface & Age Range	Binary Logistic Regression	0.886	0.002
32	Brown Staining & Juvenile Age Category	Ordinal Regression	0.882	0.002
33	Brown Staining & Anoxia	Ordinal Regression	0.858	0.002
34	Whole OHI & Charnel	Ordinal Regression	0.841	0.001
35	Yellow Staining & Juvenile Age Category	Ordinal Regression	0.831	0.001
36	Presence of Bacterial Attack & Sex	Binary Logistic Regression	0.822	0.001
37	Brown Staining & Black Death	Ordinal Regression	0.817	0.001
38	Yellow Staining & Sex	Ordinal Regression	0.806	0.001
39	Grey Inclusions & Juvenile Age Range	Ordinal Regression	0.789	0.001
40	Orange Staining & Neonate Age Range	Ordinal Regression	0.771	0.001
41	Orange Inclusions & Child Age Range	Ordinal Regression	0.766	0.001
42	Brown Staining & Orange Inclusions	Spearman's rho	0.761	0.001
43	Whole OHI & Sex	Ordinal Regression	0.756	0.001
44	Grey Inclusions & Sex	Ordinal Regression	0.704	0.001
45	Orange Staining & Juvenile Age Category	Ordinal Regression	0.692	0.001
46	Orange Staining & Child Age Category	Ordinal Regression	0.687	0.001
47	Persistence of the Periosteal Surface & State of Articulation	Binary Logistic Regression	0.684	0.001
48	Yellow Staining & Anoxia	Ordinal Regression	0.670	0.001
49	Infiltrations & Phase	Binary Logistic Regression	0.662	0.001
50	Infiltrations & State if Articulation	Binary Logistic Regression	0.662	0.001
51	Infiltrations & Sex	Binary Logistic Regression	0.657	0.001
52	Yellow Staining & Silt Soil Type	Ordinal Regression	0.650	0.001
53	Whole OHI Score & Juvenile Age Category	Ordinal	0.589	0.001

TEST NO.	COMPARISON	TEST	P-VALUE	HOLM-BONFERRONI SIGNIFICANCE THRESHOLD
		Regression		
54	Orange Staining & Phase	Ordinal Regression	0.557	0.001
55	Persistence of the Periosteal Surface & Phase	Binary Logistic Regression	0.547	0.001
56	Brown Staining & Grey Inclusions	Spearman's rho	0.530	0.001
57	Presence of Bacterial Attack & Black Death	Binary Logistic Regression	0.512	0.001
58	Yellow Staining & State of Articulation	Ordinal Regression	0.510	0.001
59	Wedl Tunnelling & Age Range	Binary Logistic Regression	0.500	0.001
60	Grey Inclusions & Non-Silt Site Assemblages	Kruskal-Wallis	0.491	0.001
61	Brown Staining & Neonatal Age Category	Ordinal Regression	0.482	0.001
62	Yellow Staining & Sand Site Assemblages	Kruskal-Wallis	0.482	0.001
63	Yellow Staining & Sand Soil Type	Ordinal Regression	0.471	0.001
64	Wedl Tunnelling & Soil Type	Binary Logistic Regression	0.468	0.001
65	Orange Inclusions & Silt Soil Type	Ordinal Regression	0.461	0.001
66	Whole OHI & Gravel Soil Type	Ordinal Regression	0.457	0.001
67	Brown Staining & Sex	Ordinal Regression	0.435	0.001
68	Presence of Bacterial Attack & Historical Site Assemblages	Pearson's X-squared	0.431	0.001
69	Orange Inclusions & Phase	Ordinal Regression	0.401	0.001
70	Yellow Staining & Gravel Site Assemblages	Kruskal-Wallis	0.395	0.001
71	Presence of Bacterial Attack & Soil Type	Binary Logistic Regression	0.381	0.001
72	Brown Staining & State of Articulation	Ordinal Regression	0.381	0.001
73	Infiltrations & Silt Site Assemblages	Pearson's X-squared	0.376	0.001
74	Whole OHI & State of Articulation	Ordinal Regression	0.374	0.001
75	Yellow Staining & Clay Site Assemblages	Kruskal-Wallis	0.363	0.001
76	Grey Inclusions & Child Age Category	Ordinal Regression	0.359	0.001
77	Yellow Staining & Charnel	Ordinal Regression	0.357	0.001
78	Whole OHI & Clay Soil Type	Ordinal Regression	0.351	0.001
79	Presence of Bacterial Attack & Charnel	Binary Logistic Regression	0.326	0.001
80	Infiltrations & Anoxia	Binary Logistic Regression	0.309	0.001
81	Presence of Bacterial Attack & State of Articulation	Binary Logistic Regression	0.298	0.001
82	Whole OHI & Juvenile Age Range	Ordinal Regression	0.296	0.001
83	Wedl Tunnelling & Black Death	Binary Logistic Regression	0.273	0.001
84	Grey Inclusions & State of Articulation	Ordinal Regression	0.265	0.001

TEST NO.	COMPARISON	TEST	P-VALUE	HOLM-BONFERRONI SIGNIFICANCE THRESHOLD
85	Yellow Staining & Grey Inclusions	Ordinal Regression	0.257	0.001
86	Wedl Tunnelling & State of Articulation	Binary Logistic Regression	0.256	0.001
87	Wedl Tunnelling & Sex	Binary Logistic Regression	0.240	0.001
88	Persistence of the Periosteal Surface & Sex	Binary Logistic Regression	0.211	0.001
89	Orange Inclusions & Clay Site Assemblages	Kruskal-Wallis	0.206	0.001
90	Orange Staining & Sex	Ordinal Regression	0.205	0.001
91	Whole OHI & Cave Deposition	Ordinal Regression	0.199	0.001
92	Orange Inclusions & Juvenile Age Category	Ordinal Regression	0.187	0.001
93	Infiltrations & Cave Deposition	Binary Logistic Regression	0.162	0.001
94	Orange Staining & Black Death	Ordinal Regression	0.156	0.001
95	Whole OHI & Silt Soil Type	Ordinal Regression	0.153	0.001
96	Orange Inclusions & Anoxia	Ordinal Regression	0.147	0.001
97	Wedl Tunnelling & Charnel	Binary Logistic Regression	0.140	0.001
98	Brown Staining & Infiltrations	Ordinal Regression	0.140	0.001
99	Orange Inclusions & Sand Site Assemblages	Kruskal-Wallis	0.140	0.001
100	Whole OHI & Historical Site Assemblages	Kruskal-Wallis	0.122	0.001
101	Brown Staining & Phase	Ordinal Regression	0.115	0.000
102	Orange Inclusions & Black Death	Ordinal Regression	0.115	0.000
103	Yellow Staining & Infiltrations	Pearson's X-squared	0.102	0.000
104	Whole OHI & Orange Inclusions	Spearman's rho	0.092	0.000
105	Brown Staining & Charnel	Ordinal Regression	0.088	0.000
106	Infiltrations & Age Category	Binary Logistic Regression	0.084	0.000
107	Infiltrations & Sand Site Assemblages	Pearson's X-squared	0.082	0.000
108	Orange Inclusions & Gravel Soil Type	Ordinal Regression	0.076	0.000
109	Wedl Tunnelling & Phase	Binary Logistic Regression	0.075	0.000
110	Orange Staining & Silt Soil Type	Ordinal Regression	0.058	0.000
111	Whole OHI & Grey Inclusions	Ordinal Regression	0.057	0.000
112	Orange Inclusions & Gravel Site Assemblages	Kruskal-Wallis	0.047	0.000
113	Orange Inclusions & Neonate Age Category	Ordinal Regression	0.038	0.000
114	Orange Staining & Anoxia	Ordinal Regression	0.037	0.000
115	Whole OHI & Persistence of the Periosteal Surface	Pearson's X-squared	0.034	0.000
116	Orange Staining & Sand Site Assemblages	Kruskal-Wallis	0.030	0.000

TEST NO.	COMPARISON	TEST	P-VALUE	HOLM-BONFERRONI SIGNIFICANCE THRESHOLD
117	Orange Inclusions & State of Articulation	Ordinal Regression	0.029	0.000
118	Orange Inclusions & Cave Deposition	Ordinal Regression	0.029	0.000
119	Whole OHI & Child Age Category	Ordinal Regression	0.027	0.000
120	Prehistoric Site Assemblages & Whole OHI	Kruskal-Wallis	0.026	0.000
121	Whole OHI & Brown Staining	Spearman's rho	0.024	0.000
122	Orange Staining & State of Articulation	Ordinal Regression	0.019	0.000
123	Orange Staining & Cave Deposition	Ordinal Regression	0.019	0.000
124	Whole OHI & Infiltrations	Spearman's rho	0.017	0.000
125	Persistence of the Periosteal Surface & Sand Site Assemblages	Pearson's X-squared	0.015	0.000
126	Orange Inclusions & Sand Soil Type	Ordinal Regression	0.014	0.000
127	Skeletal Element & Whole OHI	Ordinal Regression	0.014	0.000
128	Orange Staining & Gravel Site Assemblages	Kruskal-Wallis	0.011	0.000
129	Orange Inclusions & Clay Soil Type	Ordinal Regression	0.011	0.000
130	Orange Staining & Silt Site Assemblages	Kruskal-Wallis	0.010	0.000
131	Whole OHI & Wedl Tunnelling	Pearson's X-squared	0.008	0.000
132	Brown Staining & Site Assemblage	Kruskal-Wallis	0.007	0.000
133	Orange Staining & Sand Soil Type	Ordinal Regression	0.006	0.000
134	Infiltrations & Gravel Site Assemblages	Pearson's X-squared	0.004	0.000
135	Presence of Bacterial Attack & Specific Phase	Pearson's X-squared	0.003	0.000
136	Persistence of the Periosteal Surface & Silt Site Assemblages	Pearson's X-squared	0.002	0.000
137	Orange Staining & Clay Soil Type	Ordinal Regression	0.001	0.000
138	Orange Staining & Charnel	Ordinal Regression	0.001	0.000
139	Infiltrations & Charnel	Binary Logistic Regression	0.001	0.000
140	Whole OHI & Yellow Staining	Spearman's rho	0.001	0.000
141	Presence of Bacterial Attack & Later Prehistoric Site Assemblages	Pearson's X-squared	0.001	0.000
142	Whole OHI & Anoxia	Ordinal Regression	**0.000**	**0.000**
143	Whole OHI & Phase	Ordinal Regression	**0.000**	**0.000**
144	Whole OHI & Black Death	Ordinal Regression	**0.000**	**0.000**
145	Whole OHI & Neonatal Age Category	Ordinal Regression	**0.000**	**0.000**
146	Presence of Bacterial Attack & Anoxia	Binary Logistic Regression	**0.000**	**0.000**
147	Presence of Bacterial Attack & Phase	Binary Logistic Regression	**0.000**	**0.000**
148	Presence of Bacterial Attack & Age Category	Binary Logistic Regression	**0.000**	**0.000**

TEST NO.	COMPARISON	TEST	P-VALUE	HOLM-BONFERRONI SIGNIFICANCE THRESHOLD
149	Wedl Tunnelling & Cave Deposition	Binary Logistic Regression	**0.000**	**0.000**
150	Persistence of the Periosteal Surface & Soil Type	Binary Logistic Regression	**0.000**	**0.000**
151	Orange Staining & Gravel Soil Type	Ordinal Regression	**0.000**	**0.000**
152	Orange Inclusions & Charnel	Ordinal Regression	**0.000**	**0.000**
153	Grey Inclusions & Silt Soil Type	Ordinal Regression	**0.000**	**0.000**
154	Infiltrations & Soil Type	Binary Logistic Regression	**0.000**	**0.000**
155	Persistence of the Periosteal Surface & Specific Phase	Pearson's X-squared	**0.000**	**0.000**
156	Periosteal OHI & Whole OHI	Spearman's rho	**0.000**	**0.000**
157	Endosteal OHI & Whole OHI	Spearman's rho	**0.000**	**0.000**
158	Internal OHI & Whole OHI	Spearman's rho	**0.000**	**0.000**
159	Presence of Bacterial Bioerosion & Whole OHI	Mann-Whitney	**0.000**	**0.000**
160	Birefringence Index & Whole OHI	Spearman's rho	**0.000**	**0.000**
161	Wedl Tunnelling & Site Assemblage	Pearson's X-squared	**0.000**	**0.000**
162	Orange Staining & Orange Inclusions	Spearman's rho	**0.000**	**0.000**
163	Orange Staining & Grey Inclusions	Spearman's rho	**0.000**	**0.000**
164	Orange Staining & Infiltrations	Pearson's X-squared	**0.000**	**0.000**
165	Orange Inclusions & Infiltrations	Pearson's X-squared	**0.000**	**0.000**
166	Grey Inclusions & Infiltrations	Pearson's X-squared	**0.000**	**0.000**
167	Orange Inclusions & Silt Site Assemblages	Kruskal-Wallis	**0.000**	**0.000**
168	Grey Inclusions & Silt Site Assemblages	Kruskal-Wallis	**0.000**	**0.000**
169	Infiltrations & Clay Site Assemblages	Pearson's X-squared	**0.000**	**0.000**
170	Orange Staining & Clay Site Assemblages	Kruskal-Wallis	**0.000**	**0.000**